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Performance assessment of stabilized pavement subgrades

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by

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LIST OF SYMBOLS

Symbol	Description	Units
B	Width of footing	m
B_1	Diameter of plate used in plate load test	m
c_c	Coefficient of curvature	-
c_u	Coefficient of uniformity	-
D_0	Deflection measured under the center loading plate	mm
D_{10}	Diameter corresponding to 10% finer	mm
D_{30}	Diameter corresponding to 30% finer	mm
D_{60}	Diameter corresponding to 60% finer	mm
E_{LWD}	Elastic modulus determined using 300 mm diameter plate LWD	MPa
E_{FWD}	Elastic modulus determined using 300 mm diameter plate FWD	MPa
E_{LWD-SS}	Elastic modulus of stabilized subgrade using LWD	MPa
E_{LWD-NS}	Elastic modulus of stabilized subgrade using LWD	MPa
E_{FWD-SS}	Elastic modulus of stabilized subgrade using FWD	MPa
E_{FWD-NS}	Elastic modulus of stabilized subgrade using FWD	MPa
E_{v1}	Initial elastic modulus	MPa
E_{v2}	Reloading elastic modulus	MPa
f	Shape factor for LWD	-
K'_U	Modulus of subgrade reaction	kPa/m
K_U	Modulus of subgrade reaction corrected from bending of plate	kPa/m
K'_{U1}	Stiffness estimated from a static plate load test	kPa/m
M_r	Resilient modulus	MPa
ν	Poisson's ratio	-
s_u	Undrained shear strength	kPa

ABSTRACT

Chemical stabilization of subgrades is one of traditional technologies to provide a pavement construction platform. Laboratory test results of a typical mix design including soil strength and stiffness measurements are usually well documented in the short term. However, the long-term performance data of stabilized pavement are lack and desired for further development of this technology.

In order to address those problems, nine test sections were selected to assess engineering properties of old stabilized subgrades in Texas, Oklahoma, and Kansas. Six subgrades were stabilized with lime and three subgrades stabilized with fly ash. Ages of these stabilized subgrades ranged from 5 to 28 years. Both laboratory and in-situ tests were performed. Laboratory tests include moisture content, sieve analysis, pH test, scanning electron microscope, and unconsolidated-undrained test. In-situ tests include dynamic cone penetrometer, falling weight deflectometer, light weight deflectometer, plate load test, and soil sampling. Using engineering research international (ERI) data analysis software, the subgrade layer moduli were backcalculated based upon FWD tests results.

Soil types, pH values, mineralogical and microstructure analysis, and the improvement ratios between stabilized and un-stabilized subgrades were presented in this study. At some test sites, the field observation found that lime was not uniformly mixed with subgrades. SEM analysis shows some cementing products formed and existed in lime stabilized subgrade samples. Based on the laboratory and in-situ test results, the improved soil strength and stiffness remained after many years of construction.

CHAPTER 1. INTRODUCTION

The second Strategic Highway Research Program (SHRP2) R02 project identified and assessed 47 ground improvement technologies, including chemical, mechanical stabilization of subgrades and base courses, and other subgrade stabilization technologies. According to the Phase 1 Report of SHRP2 R02, some barriers to applying these stabilization methods are uncertainty about pavement performance and lack of long-term performance data (SHRP2 R02 Phase 1 Technology Assessments 2008).

Chemical stabilization of soft soil has been used in United States more than 60 years (Rafalko et al. 2007). The chemical additives include lime, cement, fly ash, cement kiln dust, and other nontraditional additives. Several factors influence the quality and long-term performance of stabilized subgrade, such as additive content, construction method, and environmental factors and so on. Laboratory test results of a typical mix design including soil strength and stiffness measurements are usually well documented in the short term. However, long-term performance is difficult to measure and is therefore typically relied upon for the short term. Thus, chemical stabilized subgrade is primarily considered as an approach for creating a construction platform. The long-term performance data of stabilized pavement are desired for further development of this technology. This report will address two technical problems, the lack of performance data for stabilized pavement subgrades that are more than 10 years old and lack of understanding of the factors that contribute to long-term engineering behavior of stabilized subgrades supporting pavements.

This research addressed these problems by conducting laboratory and in-situ tests for chemical (lime or fly ash) stabilized subgrades. Laboratory tests include moisture content, sieve analysis, pH test, scanning electron microscope, and unconsolidated-undrained test. In-situ tests include dynamic cone penetrometer, falling weight deflectometer, light weight deflectometer, plate load test, and soil sampling. Mineralogical and microstructure analysis were performed on stabilized subgrades. The data of strength and stiffness of stabilized subgrades were collected. A total of nine test sites are selected and located in Texas, Oklahoma, and Kansas. The selection of the test site was based on the type of subgrade, availability of old construction records, and construction year. Eight test sites were constructed more than 10 years ago, and one test site was constructed more than 5 years ago.

RESEARCH GOALS AND OBJECTIVES

One research goal is to assess engineering properties of old stabilized subgrades. The other goal is to better understand factors that contribute to changes in the engineering behavior of stabilized subgrade supporting pavement.

The main objectives of this research are to:

- Investigate chemical components and microstructure of in service stabilized soils
- Investigate in-situ stiffness of the stabilized and natural subgrades
- Determine stiffness improvement ratio between stabilized and natural subgrades

RESEARCH BENEFIT AND SIGNIFICANCE

This research will result in creating case studies for engineers and researchers to better understand long-term performance of chemical stabilized subgrades and encouraging pavement designer to incorporate chemical stabilized subgrades into pavement design. Advantages and disadvantages with other stabilization technologies will be compared based on literature review of SHRP2 R02 project.

BACKGROUND OF SHRP2 R02 PROJECT

Strategic Highway Research Program Project Number R02 (SHRP2 R02) have identified more than 47 geoconstruction technologies for transportation infrastructure projects. The objectives of SHRP2 R02 are to achieve:

- Rapid renewal of transportation facilities,
- Minimal disruption of traffic, and
- Production of long-lived facilities.

Phase 1 of the project focuses on identifying those geotechnical materials, systems, and technologies that best achieve the SHRP2 Renewal strategic objectives (SHRP2 R02 Phase 1 Technology Assessments). It consists of task 1 through task 6. One of the key outcomes is to identify technical and non-technical issues that results in preventing further development of the technology. Technical issues are summarized in Table 1 in Phase 1 report. The degree of interference with widespread were accessed and rated using four levels (high, medium, low, and none).

Chemical stabilization of subgrades and base courses is one of these technologies that is use to provide a pavement working platform and prolong pavement service life. Because of performance uncertainty and absence of long-term performance data, pavement engineers are not certain that chemical stabilized subgrade can provide sufficient support as a subbase layer in its design life. The structural benefit of stabilized subgrade is generally not considered in most pavement design codes (e.g. AASHTO 1993, AASHTO 1998).

Phase 2 of the project includes evaluations of the effectiveness of mitigation measures; a catalogue of materials and systems for rapid renewal projects; guidance for design and QC/QA procedures; methods for estimating costs; and sample specifications for the identified geotechnical materials, systems, and technologies. It consists of task 8 through task 13. The task 9, task 10, and task 12 are summarized as follows:

Task 9: Comprehensive Technology Summary

The task 9 is a comprehensive summary of chemical stabilization subgrade including applications, case histories, QC/QA programs, cost information, and specifications. The task 9 document is Appendix A.

Task 10: Assessment of Design Methods and QC/QA Procedure

Design guidance and QC/QA programs are compiled and reviewed. Input and output of design parameters are summarized. Detailed design procedures are presented and accessed based on performance criteria, subsurface conductions, loading conditions, etc. QC/QA programs are accessed based on accuracy and precision, adequacy of coverage, implementation requirements, and applicability to method approach specifications. The task 10 document is Appendix B.

Task 12: Assessment of Existing Specification

It compiles and assesses the existing construction method and performance specifications from DOTs, AASHTO, etc. The task 12 document is Appendix C.

Table 1. Summary of technology issues (from Phase 1 of SHRP2 R02)

No.	Item	Degree of interference with widespread use (High, Medium, Low, None)
1	Lack of simple, comprehensive, reliable, and non-proprietary analysis and design procedures	1
2	Costs for design, construction, QC/QA, and/or maintenance	2
3	Construction time	1
4	Time from installation to full effectiveness	1
5	Lack of established engineering parameters and/or performance criteria	1
6	Lack of effective QA/QC procedures	0
7	Lack of easy-to-use tools for selecting technology	1
8	Technology immaturity	1
9	Need for a specific project delivery method, e.g., (1) design-bid-build, (2) pre-bid alternatives, (3) post-bid alternatives (V.E.), (4) design-build, (5) design-build-maintain	0
10	Lack of site characterization information	2
11	Performance uncertainty	2
12	Lack of long-term performance data	1
13	Environmental impacts of the technology	3
14	Lack of accessible case histories	0
15	Construction loads	1
16	Vibrations	0

3-High, 2-Medium, 1-Low, and 0-None

THESIS ORGANIZATION

This thesis is organized to 6 chapters. Chapter 2 is a literature review about testing methods used in this study, design, quality control and assurance, and case studies for chemical stabilized soil. Chapter 3 describes both field and laboratory test methods performed at site and in geotechnical research lab at Iowa State University. Chapter 4 provides nine case studies conducted in TX, OK, and KS. It covers site description, and in-situ and laboratory test results at each site. Chapter 5 summarizes the key findings from this study. Recommendations for future researchers and pavement engineers are provided in Chapter 6.

CHAPTER 2. BACKGROUND/LITERATURE REVEIW

In this chapter, several previous studies are reviewed for long term performance of chemical stabilized subgrades. A literature review of design methods, quality control and assurance, and in-situ testing methods are also presented.

LONG-TERM PERFORMANCE OF CHEMICAL STABILIZED SUBGRADES

This section summarizes three papers that focus on evaluations of long-term performance of chemical stabilized subgrades. The first study by Little et al. (1995a) focused on investigations of structure improvements of stabilized bases and subgrades after several years of service life. A total of 30 test sites in Texas with lime stabilized subgrades were investigated. The falling weight deflectometer (FWD) test results were backcalculated to determine the natural and stabilized subgrade modulus. The dynamic cone deflectometer test was applied to verify measurements from FWD tests. At all but one sites, backcalculated moduli of stabilized subgrades were equal or greater than 200 MPa. Typically, a good quality of aggregate base is 200 MPa. For 27 out of 30 test sites, backcalculated FWD moduli showed that the modulus ratio between lime stabilized and natural subgrades was greater than 3. The authors stated that, if the structural benefit of stabilized subgrades needs to be considered in pavement design, the modulus ratio of 3 is the minimum value. The structure improvement of stabilized subgrades remained several years after construction.

The second study by Hopkins et al. (2002) reported on an evaluation of the long-term performance of chemical stabilized subgrades in Kentucky. A total 20 test sections were selected and the subgrades were stabilized using lime or cement. The laboratory and field tests included grain size, index property, moisture content, specific gravity, unconfined triaxial compression test, in-situ CBR, standard penetration test, and falling weight deflectometer. Some key findings are summarized as follows:

- The soil types of natural subgrades were modified from silts (ML) to sandy silts (SM) after treatment. The clay faction of natural subgrades was also reduced.
- In-situ CBR of lime stabilized subgrades were 14 times of the natural subgrades.
- Moisture content of top un-stabilized subgrades had a value of 3-4% greater than moisture content of top stabilized subgrades. That indicates that stabilized subgrades help mitigate or eliminate the “soft zone” on the pavement.

- The FWD modulus of stabilized subgrades was greater than that of natural subgrade. The FWD moduli ranged from 19- 455 MPa (2,700 - 66,100 psi) for natural subgrades and 149-896 MPa (21,600 - 130,000 psi) for stabilized subgrades.
- The FWD modulus of the granular base rested on the stabilized subgrade was much greater than that value of the granular base rested on the un-stabilized subgrade. The modulus of the granular base will increase as increasing of the modulus of underlying the stabilized subgrade.

The third study by Jung et al. (2008) investigated the performance of six lime kiln dust stabilized subgrades in Indiana using both the laboratory and field tests. These stabilized subgrades were constructed in between 1996 and 2002. Comparison was made between stabilized and natural subgrade in moisture content, fines content, soil type, pH value, CBR, and $M_{R.}$ Key findings are the following:

- The fines content of natural subgrades was reduced by 20 to 40% after treatment.
- The water content of stabilized and natural subgrade was uniform at each test site.
- The types of natural subgrades were modified from slity or clayey to non-plastic slity sand for stabilized subgrades.
- The pH values of natural subgrades ranged from 7.5 to 8.0, while the pH values of stabilized subgrades ranged from 8.5 to 11.0. The high pH of stabilized subgrades indicated that the effect of lime still remained in stabilized subgrades.
- The average CBR of natural subgrades increased 500-1500% after treatment

The LKD stabilized subgrades performed well after 5-11 years. The authors stated that the uniformity of stabilized subgrades was questionable. Improvement of quality control program was recommended to ensure that the long-term performance of LKD treated subgrades.

DESIGN METHODS

Lime Stabilization of Subgrades and Bases

Determining lime content is the primary objective of mixture design for lime stabilization. The optimum lime content is dependent on how the stabilized material will be used and the soil constituents. The design objects may involve a reduction in plasticity, construction expediency, or permanent engineering changes which affect the strength/stiffness of the mixture and performance of the pavement which contains the treated layers. Mixture preparation, specimen preparation, curing conditions, and testing are four factors considered as part of a laboratory testing program. Special testing is required for sulfate-bearing clay to prevent deleterious sulfate-induced heave. Table 2 shows the general stabilizing effect of lime on different soil types.

Table 2. General stabilizing effects of lime on different soils types (from Winterkon and Pamukcu 1990)

Type of Soil	Untreated					Lime Treated[a]				
	Triaxial	*CBR*	*R-Value*	*k-Value*	*Cohesiometer*	*Triaxial*	*CBR*	*R-Value*	*k-Value*	*Cohesiometer*
Heavy clay	5.5	2	20	100	—	3.2–3.5	15–30	55–69	250–350	350–850
Light clay	4.5	5	35	150	—	2.9–3.4	20–40	60–75	300–400	450–700
Sandy clay	3.7	12	50	200	—	2.4–3.0	35–60	65–80	400–500	550–850
Granular soil *PI* = 8+	3.2	30	65	250	—	1.5–2.7	50–75	70–80+	450+	650+
Clay gravel *PI* = 6 to 10	2.6	50	75	400	—	1.0–1.6	70–100+	80+	500+	800+

[a] Based on use of 4–6 percent lime for clay soils and 2–4 percent for granular and clay-gravel types. Triaxial and cohesiometer values are based on approximately 18 days of laboratory curing, CBR on 4 days curing (soaked), and *R*-value on about 2 days curing. The stability values of lime-treated specimens increase markedly with longer or accelerated curing: e.g., curing CBR specimens for 2 days at 120°F prior to soaking will nearly double the CBR values. This accelerated curing would correspond approximately to 30 to 45 days of summer field curing.

Because applications of lime can be broad in stabilization, several mix design methods have been developed. According to TRB (1987), these methods are:

1. California procedure (Terrel et al. 1979)
2. Eades and Grim procedure (Eades et al. 1966)
3. Illinois procedure (Terrel et al. 1979)
4. Oklahoma procedure (TRB 1987)
5. South Dakota procedure (TRB 1987)
6. Texas procedure (AASHTO T-220)
7. Thompson procedure (Thompson 1970)
8. Virginia procedure (VTM-11 Virginia Test Method for lime stabilization)

An example of one of these methods, the Texas procedure, is summarized below.

Step 1: Based on the grain size and PI data, the lime percentage is determined by using the recommended amounts of lime for stabilization of subgrades and bases (Terrel et al. 1979); that graph is shown in Figure 1.

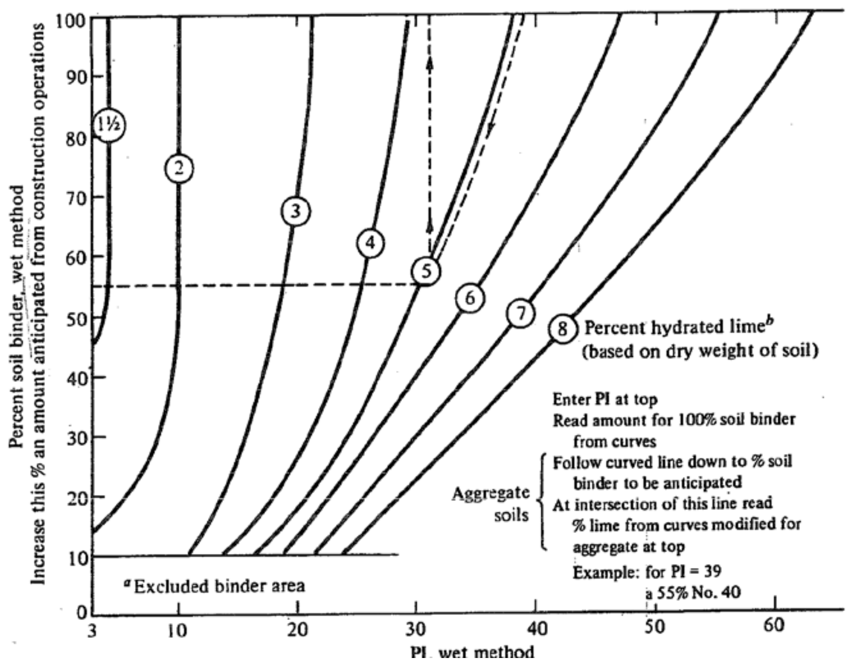


Figure 1. Recommended amounts of lime for stabilization of subgrades and bases (from Terrel et al. 1979)

Step 2: Optimum moisture and maximum dry density of the mixture are determined in accordance with AASHTO T-212 or Tex-113-E.

Step 3: Test specimens 6 in (15.2 cm) in diameter and 8 in. (20.3 cm) in height are compacted at optimum moisture content to maximum dry density.

Step 4: All specimens are placed in a triaxial cell and cured in the following manner:

a: Cool to room temperature .

b: Dry at temperature not exceeding 60° C (140° F) for about 6 hr until one-third of the molding moisture is remove.

c: Cool for at least 8 hr.

d: Subject specimens to water exposure via capillary action for 10 days (AASHTO T-212).

Step 5: The cured specimens are tested in unconfined compression with AASHTO T-212 section 7 and 8 or Tex-117-E.

The design process flow chart is shown in Figure 2. Two design criteria are used: (1) pavement structural behavior and (2) durability requirement. In addition, swell needs to be reduced to a satisfactory level for lime-modified soil.

To deal with sulfate induced problems with lime stabilized soils, the National Lime Association (2000) provides guidelines as following:

Sulfate levels too low to be of concern: The total level of soluble sulfates is below 0.3% (3000 ppm). The general construction procedure is followed, due to a low risk of harmful reaction.

Sulfate levels of moderate risk: The total levels of soluble sulfates are between 0.3% (3000 ppm) to 0.5% (5000 ppm). During construction, water content should be at least 3% to 5% above optimum for compaction. Mellowing period may be extended longer than 72 hours.

Sulfate levels of moderate to high risk: The total levels of soluble sulfates are between 0.5% (5000 ppm) to 0.8% (8000 ppm). The same mix design and construction can be followed as same as soil containing 0.3-0.5 % sulfate. Additionally, the laboratory test is recommended to determine swell potential before treatment, which also helps find the required period of mellowing between mixing and compaction.

Sulfate levels of high and unacceptable risk: The total levels of soluble sulfates are greater than 0.8% (8000 ppm). Due to high sulfate levels, treatment requires lime slurry, mixing, mellowing, curing water contents of 3%-5% above optimum for compaction, and mellowing period may be extended longer than 72 hours. The double application of lime may be applied too.

Although the benefits of improved soil properties are not considered into most current design approaches in United States, a study conducted by Qubain et al. (2000) shows that lime treated subgrade soil can be successfully incorporated into pavement design with economic benefit by increasing the strength of subgrade. Three approaches were applied in this study: (1) utilizing an effective resilient modulus for the lime treated subgrade, (2) applying a very conservative CBR of 15 to account for lime stabilization, and (3) considering the lime stabilized subgrade as subbase and assigning it a structural–layer coefficient. Little information is available in the literature, however, that documents the long-term performance of stabilized soils for permanent foundation materials.

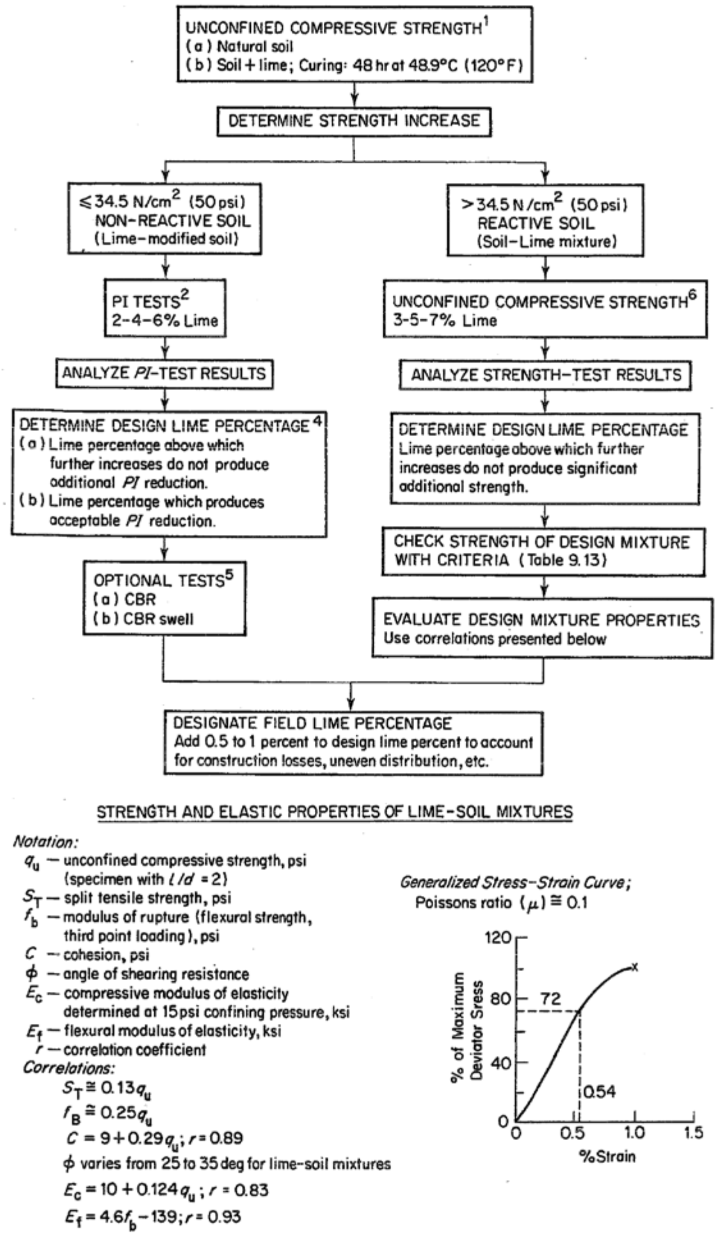


Figure 2. Mixture design for lime-treated soils according to Thompson procedure (from Winterkorn and Pamukcu 1990)

Fly Ash Stabilization of Subgrades and Bases

Class C fly ash is recommended to stabilize fine-grained plastic soils such as clay, as well as coarse-grained soil (ACAA 2008). Some factors are important when develops the mix design procedure for stabilization applications utilizing self-cementing ash. Based on ACAA (2008), firstly self-cementing ash hydrates at a much more rapid rate than Portland cement, and 2-hour delay in compaction can result in a decrease in maximum density of up to 1.6 KN/m^3 (10 pcf) or more. Secondly, moisture content influences the compressive strength. To deal sulfate attack problems for stabilized materials, fly ash with the high sulfate concentrations should be avoided.

A laboratory study by Ferguson (1993) recommended that a fly ash content was 16% for mixing with subgrade materials to obtain maximum California Bearing Ratio. No standard test procedures currently exist for the design of material stabilized with self-cementing ash (ACAA, 2008). However, an effective procedure can be used to determine moisture-density and moisture-strength relationships of the stabilized material, based on adaptation of ASTM C593 (Fly Ash and Other Pozzolans for Use with Lime) and ASTM D 1633 (Compressive Strength of Molded Soil-Cement Cylinders). The design procedure follows:

1. Blend soil, fly ash and water to make a minimum of five test specimens. Moisture contents of the specimen should be up to 10% below to 6% above the optimum moisture content for maximum density. The specimens have a height-to-diameter ratio of 1.15.
2. Compact specimens over a wide range of moisture contents. Use specified compaction time delay (<2 hours) and 102-mm (4.0-inch)-diameter by 117-mm (4.625-inch)-high mold. Standard Proctor compactive energy or modified proctor compactive energy may be used. Alternatively, it can use specimens with 50.8 mm (2 in.) in diameter by 50.8 (2 in.) high. Advantages for using these specimens are material and time saving. Additionally, the test results obtained from those specimens are very close with using the standard Proctor specimens (Oflaherty et al. 1963).
3. Cure test specimens for a period of 7 days at 38°C (100°F) in accordance with ASTM C593, and
4. Determine compressive strength of specimens.

Modification of the compaction procedures may be required for mix designs of granular materials stabilized with ash. For stabilized pavement section or other applications where a higher degree of stabilized is desired, additional laboratory tests needs to conducted assess properties of the stabilized materials required for specific design procedures. Stabilized granular material to be used for pavement base course or subbase tests can be evaluated through ASTM C593 to assess the freeze-thaw durability of the stabilized materials.

QUALITY CONTROL AND QUALITY ASSURANCE

Quality control and assurance programs for chemical stabilization of subgrades and base courses are discussed according to various stages of construction.

Prior to Stabilizer Application

Sampling of loose processed materials is used to check gradation of the materials and ensure the oversize materials are limited to the specification target value. For controlling pulverization in cement stabilization, a sieve analysis is typically performed using a No. 4 sieve. For lime stabilization, the 1-inch and No. 4 sieves are designated for controlling pulverization. Gradation requirements for fly ash and bitumen stabilized soil are detailed in Army and Air Force (1994).

During Stabilizer Application

Stabilizer additive content tests are performed transversely across the pavement and at various depths within the stabilized layer to assess the mixing effectiveness. Chemical analysis, phenolphthalein test, and visual inspection are used to estimate the stabilizer content. Chemical analysis can be expensive and slow, however. According to TRB (1987), a phenolphthalein test on a face cut in the stabilized layer is used as a “quick” test to determine the presence of lime or cement instead of the exact content of the stabilizer. A reddish-pink color develops if lime is present in the soil, for example.

Trenches are dug and a visual inspection is made to assure uniformity of the mixture. Uniformity is checked throughout the depth and across the width of the pavement. The phenolphthalein test can also be used to check the uniformity of the mixture in the field.

Moisture content measurements are obtained at various stages of construction. Moisture content is commonly determined by either oven-dry or nuclear gauge methods. The hand squeeze test is not frequently mentioned, but often used to estimate suitable moisture content. Although the hand-squeeze test cannot replace the standard moisture content test, it assists with improved process control. The control of moisture content is important in achieving required pulverization and hydration for lime, cement, and fly ash stabilization. Bitumen stabilization has specified requirements for moisture content.

Field personnel should be aware of the depth of the stabilized layers both before and after compaction. Depth of mixing can be checked as the same time as uniformity, and should be checked routinely during mixing operations.

In-situ Verification

Nuclear gauge testing is common for checking if the required dry density is obtained after compaction. Clegg impact hammer and dynamic cone penetrometer (DCP) tests are two methods to measure the stability of the stabilized subgrade at various times upon completion of stabilization. In addition, undisturbed samples following a laboratory curing process can be used to determined unconfined compressive strength and resilient modulus in the laboratory.

IN-SITU TESTING METHODS

Dynamic Cone Penetrometer

Dynamic cone penetrometer (DCP) is an economical, rapid and easy operated device to measure in-situ soil strength and stiffness of subgrades and base layers. Because of these advantages, this test has been applied extensively in Australia, South Africa, the United States, the United Kingdom and many other countries (Chen et al. 1999). Figure 3 is a schematic sketch of DCP. The operation is to drop 8 kg weight hammer on anvil, then the cone will penetrate into subgrades or granular layers. This process will repeat until reaching to the desired depth or refusal. The data of drops and penetration depth is recorded during testing. The test results of the penetration index (PI) are calculated and expressed in terms of mm/ blow (in./blow).

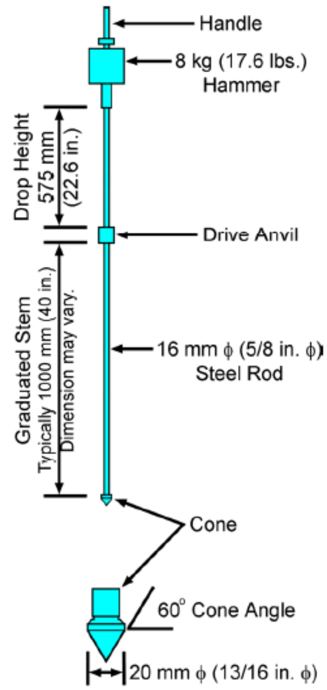


Figure 3. DCP apparatus (from Illinois DOT, 2005)

Burnham and Johnson (1993) summaries four applications of DCP testing:

- Preliminary soil surveys. DCP testing can be operated to locate areas of weak soil before construction (e.g. collapsible soil)
- Construction control. It can be used as a QC/QA method to monitoring construction of pavement subgrade and base, and verify the uniformity and level of the compaction.
- Structure evaluation of existing pavements. The expectancy of pavement life can be predicted.
- Future applications. This testing method can be a substitute for final testing rolling of grades before pavement placement. It is also applicable to measure the frost/thaw depth in cold climate pavements during the spring months.

The study of correlation of CBR and DCP has been conducted by many researchers. The following Equation (1) was developed by the U.S. Army Corps of Engineers for correlation between CBR and DCP (Webster et al. 1992):

$$log\ (CBR) = 2.47\text{-}1.12\ log(DCP) \qquad (1)$$

This equation was also adopted in ASTM D 6951 "*Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications.*" Several correlations were studied by Livneh (2007), as shown in Table 3.

Table 3. Summary of DCP-CBR Correlation (from Livneh 2007)

Type of Material	Correlation Equation	Reference
All types with DCP≥ 10	log(CBR) = 2.56-1.16 log(DCP)	Harrison (1989)
All types with DCP< 10	log(CBR) = 2.54-1.12 log(DCP)	Harrison (1989)
All types (except CL and CH)	log(CBR) = 2.47-1.12 log(DCP)	Webster et al. (1992)
All types	log(CBR) = 2.44-1.07 log(DCP)	Ese et al. (1994)
CH only	log(CBR) = 2.54-1.0 log(DCP)	Webster et al. (1994)
CL with CBR< 10% only	log(CBR) = 3.54-2.0 log(DCP)	Webster et al. (1994)
All types	log(CBR) = 2.62-1.27 log(DCP)	Smith and Pratt (1983)
All types	log(CBR) = 2.56-1.15 log(DCP)	Kleyn (1975)
All types	log(CBR) = 2.26-0.95 log(DCP)	Seyman (2003)

CBR is also correlated with resilient or elastic modulus, as shown in Equation (2) (AASHTO 2002).

$$E\ (psi) = 2555\ CBR^{0.64}, \qquad E\ (MPa) = 17.6\ CBR^{0.64} \tag{2}$$

Falling Weight Deflectometer

Falling Weight Deflectormeter (FWD) is a dynamic loading, non-destructive test, and widely applied in the United States to evaluate pavement condition. NCHRP (2008) investigated FWD ownership in 45 state highway agencies. Most of FWD equipments were manufactured by Dynatest, JILS, and KUAB. Crovetti et al. (1988) compared the equipment of KUAB 2M with Dynatest 800. The KUAB 2M uses seven deflection transducers to measure pavement deflection rather than seven geophones equipped in Dynatest 800. Additionally, a two-mass system is used in KUAB 2M to provide a more reproducible load pulse than one mass system. Some key features of two FWDs are summarized in Table 4.

Table 4. Equipment specification for two FWDs (from Crovetti 1988)

	KUAB 2M	**Dynatest**
Load range	70-150 kN	7-125 kN
Load rise time	28 ms	Variable
Load duration	56 ms	25-30 ms
Load generator	Two-mass system	One mass system
Load plate	Segmented or nonsegmented with rubberized pads (300 and 450 mm diameter)	Geophones with or without dynamic calibration device
Defelction sensor positions	0-1.8 m	0-2.25 m
Number of sensors	7	7
Defelction sensor range	5 mm (200 mils)	2 mm (80 mils) or 2.5 mm (100 mils)
Defelction resolution	1 μ (0.04 mils)	1 μ (0.04 mils)
Relative accuracy	2 μ ± 2 %	2 μ ± 2 %
Test sequence	Unlimited, user selected	8 drops
Test time sequence (4 loads)	35 s	25 s

The advantages and disadvantages for applying impulse load were described in NHI (1994) and Thum (1995). Advantages are (1) the actual wheel loading is simulated, (2) the test can be used to measure deflection base and joint/crack load transfer, and (3) it can be run in a short time. Disadvantages are: (1) the initial cost of equipment is high, (2) the device should be completely stationary to perform test, and (3) the analysis is only based on peak static deflection basins due to poor understanding of dynamic response of the pavement.

According to ERI (2009), the rigid pavements backcalculation is based upon Area method that assumes a two layer system of PCC slab. An elastic subgrade modulus (E_{sg}) and a dense liquid modulus of subgrade reaction (k) are estimated for a composite subgrade layer. The subgrade parameters are calculated based on the deflection basin AREA calculation from sensors located 0 cm (0 in.), 31 cm (12 in.), 71 cm (24 in.), and 91 cm (36 in.) from the load center.

For the flexible pavements, the backcalculation is based on the multi-layer elastic model. A deflection basin is calculated using inputs (e.g. thickness, seed values, and Poisson's ratio), which attempts to match with the actual deflection basin. The program will repeatedly run with adjusting inputs of layer modulus values each time, until the total absolute difference between the calculated deflection and measured deflection is smaller than 10%. Meanwhile the ELSYM5 is used as a subprogram to make the deflection basin calculations. Modulus of subgrade backcalculation uses the AASHTO (1986) method.

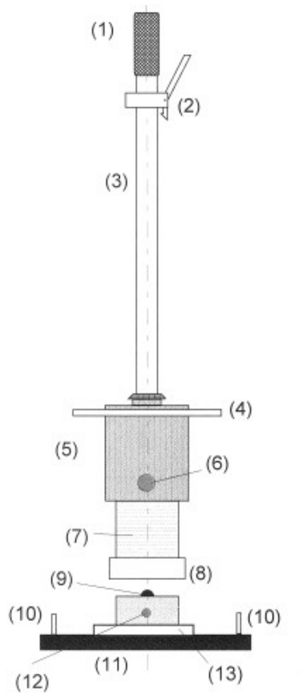
Plate Loading Test

The plate load test (PLT) can be conducted either on top of subgrades or base courses to determine soil bearing capacity and subgrade reaction. The reaction force from a piece of heavy equipment is transferred using a hydraulic jack acting against heavy mobile equipment or a frame. During the test, the applied load and the corresponding vertical displacement of the plate are recorded. The load-deflection relationship of soil can be plotted and evaluated, using the average deflection of the plate recorded by three linear voltage displacement transducers. Non-Repetitive static and repetitive plate load test are both presented in ASTM standards to determine the subgrade reaction (ASTM D 1195 and ASTM D 1196).

Zimper (1961) conducted a study about plate bearing test performed in conjunction with the flexible pavement design in Florida. However, it is a time consuming and labor intensive test (NCHRP 1996). According to Fwa (2006), the test is not performed extensively in U.S. for highway construction, because that the large magnitude of load is required and the loading mode is not same as actual traffic.

Light Weight Deflectometer

Light weight deflectometer is a rapid and portable test to measure strength and stiffness of subgrade or base. This method can serve as a QA/QC method using in geotechnical construction (e.g., roadway, dam, and soil improvement). The main manufacturers of LWD are Zone, Kero, and Dynatest. Generally a LWD device consists of three parts: (1) a loading plate, (2) a geophone or accelerometer to determine deflection, and (3) a load cell or calibrated drop height to determine plate contact stress (Vennapusa and White 2009). Figure 4 shows a schematic sketch of Zorn LWD (MN DOT 2009).



1. Handle Grip
2. Top Fix and Release Mechanism
3. Guide Rod
4. Falling Weight Grip
5. 10-kg (22-lb) Falling Weight
6. Lock Pin
7. Steel Spring
8. Anti-Tipping Fixture
9. Load Center Ball
10. Carry Grip
11. Loading Plate
12. Cable

Figure 4. Schematic drawing of Zone LWD (from Mn DOT 2009)

The elastic modulus E_{LWD} is determined based on elastic half-space theory. The influence depth is about one time of the plate diameter (Fleming 2001). The applied force on a surface is assumed ideally to be constant for Zone LWD. Equations (3) is used for calculate the applied force.

$$F = \sqrt{2mghC} \tag{3}$$

Where:

F=Applied force (N)

m=mass of falling weight (kg)

g=acceleration due to gravity, 9.81 (m/s^2)

h=drop height (m), and

C=material stiffness constant (N/m)

LWD can be an alternative method for PLT, due to its advantage. But some issues of LWD test has been found and discussed in Hossain and Apeagyei (2010). The poor correlation has been reported between compaction levels and LWD for controlling compaction. Using different test devices, high variability was existed in measured modulus for tests on same material with different devices. For example, the moduli measured with the Zorn LWD were 1.75 to 2.2 times higher than that of Keros LWD (White et al 2007). Correlation between LWD and FWD moduli varied (Livenh and Gold berg 2001, and Nazzal et al 2004). Vennapusa and White (2009) conducted an extensive literature review on several factors to influence E_{LWD} measurement, including size of loading plate, plate contact stress, type and location of deflection sensors, plate rigidity, load transducer, and load rate and stiffness of buffer.

CHAPTER 3. TEST METHODS

Field and laboratory tests were conducted to investigate pavement performance, characterize soil engineering properties, and analyze soil morphology and chemical composition. Field and laboratory tests are discussed as follows:

FIELD TESTS

Field tests performed were real-time kinematic-global positioning system (RTK-GPS), dynamic cone penetrometer (DCP), falling weight deflectometer (FWD), light weight deflectometer (LWD), plate load test (PLT), and boring and sampling.

Real-Time Kinematic-Global Positioning System

RTK-GPS was employed to record in-situ test locations with spatial coordinates (x, y and z). Precision of the system can reach approximately 10 mm horizontal and 20 mm vertical (White et al. 2010).

Dynamic Cone Penetrometer

Dynamic cone penetrometer (DCP) tests were performed to show pavement profiles and measure subgrade strength in according with ASTM D6951-03 "*Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications.*" Holes with a diameter of 38 mm (1.5 in.) were drilled into the pavement layers before testing (Figure 5). Extension rods were added to DCP to a depth of 1.5 m (59 in.). Dynamic penetration index (DPI) and California bearing ratio (CBR) of subgrades can be calculated. To calculate CBR values, Equation (4) is applied:

$$\mathrm{CBR} = \frac{292}{(\mathrm{DCPI})^{1.12}} \tag{4}$$

The weighted average CBR were calculated for each test points at all sites.

Figure 5. (a) Drilling a hole prior to DCP test, (b) dynamic cone penetrometer test

Falling Weight Deflectometer

FWD tests were conducted on ACC and PCC surfaces with a KUAB 2M-FWD 150. The applied load is transmitted to a circular loading plate. The loading plate has 300 mm (12 in.) diameter. One seating drop followed by other three test drops were applied using impacts loads of 27 KN (6000 lb), 40 KN (9000 lb), 54 KN (12000 lb), and 72 KN (16000 lb). The deflections were measured using seven deflection sensors mounted on a raise-lower bar and the actual applied force was measured using a load cell. The sensor distances from the center of loading plate (D_0) are summarized in Table 5. The modulus of both stabilized subgrade, and natural subgrade were backcalculated based on deflection data using ERI data analysis software (ERI 2009). Temperature measurements of pavement were recorded at different depths through small drilled holes before FWD testing. The equipment of KUAB FWD is shown in Figure 6.

Kim et al. (1995) conducted a study about temperature correction of deflections, and Equation (5) was presented to covert deflections (D_0) to a reference temperature as following

$$D_{68} = 10^{\alpha(68-T)} * D_T \quad (5)$$

Where:

D_{68}=adjusted deflection to the reference temperature of 20 ^{0}C (68 ^{0}F)

D_T=deflection measured at temperature T (^{0}F)

α= 3.67 $\times 10^{-4} \times t^{1.4241}$ for lane center

t=thickness of AC layer (in.), and

T=the AC layer middepth temperature (^{0}F) at time of FWD testing

Table 5. Position of seven deflection sensors

Deflection Sensors	Offsets from center of loading plate
D1	15 cm (6 in.)
D2	31 cm (12 in.)
D3	46 cm (18 in.)
D4	71 cm (24 in.)
D5	91 cm (36 in.)
D6	122 cm (48 in.)
D7	152 cm (60 in.)

Figure 6. Kuab falling weight deflectometer

Light Weight Deflectometer

Light weight deflectometer tests were performed on the top base layer, stabilized subgrade, and natural subgrade to analyze stiffness and strength. The tests were conducted using a 300 mm diameter plate and a drop height of 0.5 m, following manufacturer recommendations (Zorn 2003). The average deflection was measured after three seating drops followed by three test drops. The following equation was used to calculate E_{LWD} (Vennapusa and White 2009):

$$E = \frac{(1-v^2)б_0 a}{d_0} f \qquad (6)$$

where:

E = elastic modulus

d_o = measured settlement,

v = Poisson's ratio (assumed as 0.4),

$б_0$ = applied stress,

a = plate radius

f is the shape factor depending on stress distribution. It is assumed as a value of 2 for stabilized subgrade, a value of π/2 for natural subgrade, and a value of 8/3 for base layer. Figure 7 shows LWD testing.

Figure 7. Light weight deflectometer test

Plate Load Test

A static plate load test was performed on surface subgrade to measure load-deformation response and determine elastic modulus of stabilized subgrade in accordance with ASTM D 1195 "*Standard Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements.*" A static load was applied on a 300 mm diameter plate. The pavement deflections were calculated using data measured by three 50 mm linear voltage displacement transducers, while the actual applied load was measured by a load cell. Equation (3) was applied to determine initial (E_{V1}) and re-load (E_{V2}) modulus, and the deformation reading was taken from 0.2 to 0.4 for stabilized subgrades. Using Equation (**7**), the modulus of subgrade reaction for using 762 mm (30 in.) diameter plate was converted (Terzaghi 1955). According to AASHTO T 222-81, a value of uncorrected modulus of soil (k′u) was calculated using Equation (8). Correction of K'_U value for bending of the plate was made using the curve in Figure 8. PLT testing is shown in Figure 9.

$$K'_U = K'_{U1}\frac{B+B1}{2B} \quad \textbf{(7)}$$

B_1=side dimension of a square plate used in load test (m)

B=width of footing (m),

K'_U=modulus of subgrade reaction (kPa/mm), and

K'_{U1}=stiffness estimated from a static plate load test (kPa/mm)

$$K'_{U1} = \frac{69.0 \text{ kPa (psi)}}{\text{average deflection}} \quad (8)$$

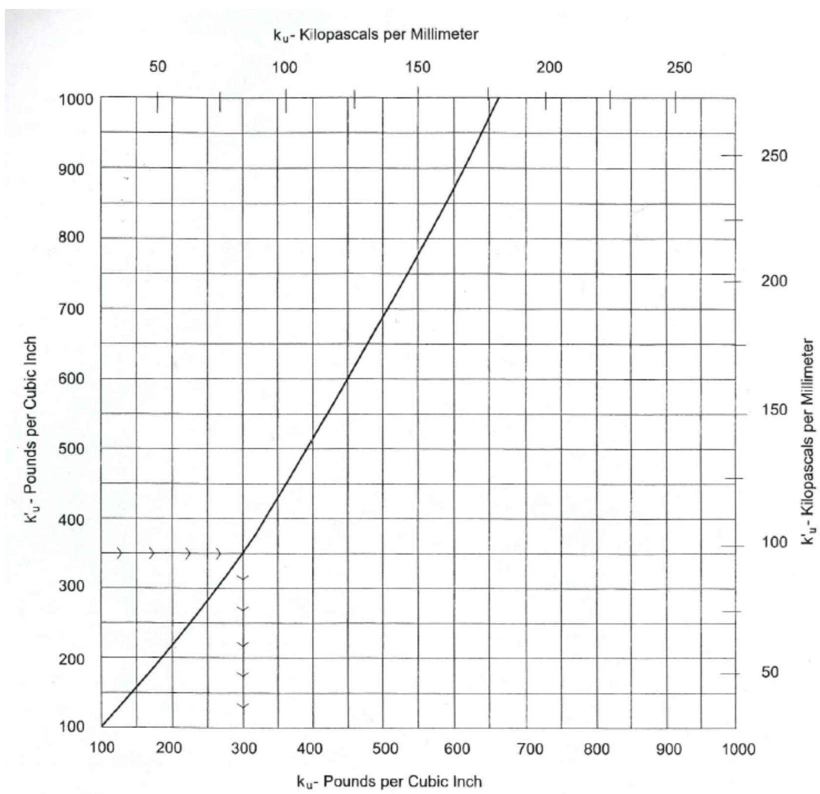


Figure 8. Correction of k′$_U$ for bending of the plate (from AASHTO T 222-81)

Figure 9. Plate load test

Boring and Sampling

A pavement coring equipment with 355 mm (14 in.) inside diameter was used to drill PCC and Asphalt pavement (Figure 10). Shelby tubes with 71 mm (3 in.) diameter were hydraulically and vertically pushed into subgrades to obtain the undisturbed stabilized samples to perform unconsolidated-undrained triaxial compression tests (Figure 10). Bag samples were collected for bases, natural subgrades and stabilized subgrades. The stabilized subgrade samples were collected at 50 to 76 mm (2 to 3 in.) intervals. Natural subgrades were collected from underlying stabilized subgrade layer and in ditch areas adjacent to the test locations. All samples were sealed in plastic bags or buckets and transported to ISU soil research lab for further laboratory tests. Figure 11 shows top the lime stabilized subgrade and about 300 mm (12 in.) pavement core.

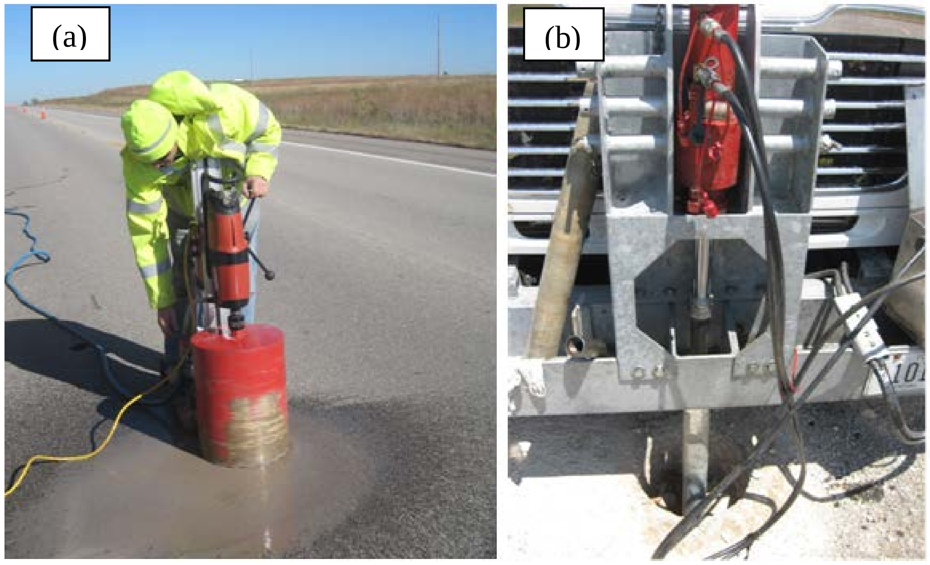


Figure 10. (a) Paving coring (b) collecting of undisturbed Shelby tube sample

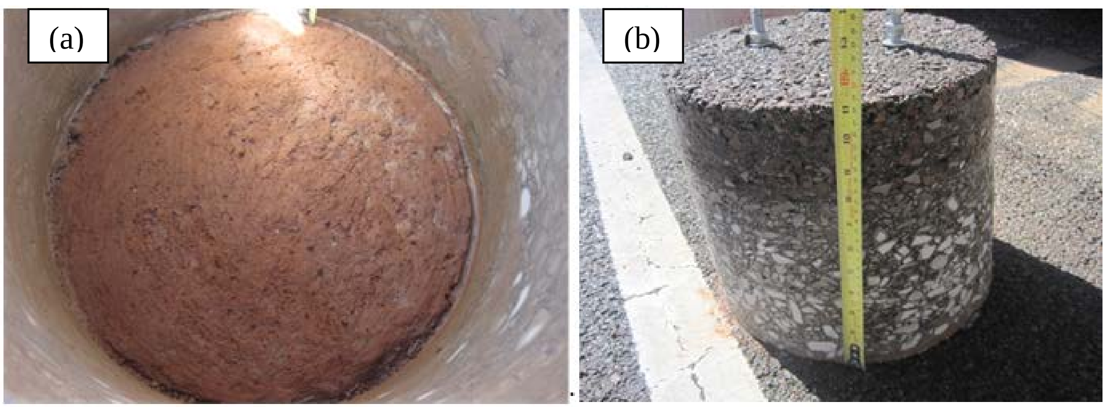


Figure 11. (a) Top stabilized subgrade (b) pavement core

LABORATORY TESTS

Laboratory tests were conducted including: moisture content, gradation, and index properties, pH test, unconsolidated-undrained triaxial compression tests (UU), and scanning electron microscope (SEM).

Moisture Test

The moisture content of soil samples was determined following ASTM D 2216-09 "*Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*." The moisture contents of Shelby tube and bag samples were measured within one week of transported to the laboratory.

Particle Size Distribution Analysis and Index Properties

Bag samples of subgrade and base were tested to determine their particle size distribution in accordance with ASTM D422-63 "*Standard Test Method for Particle-Size Analysis of Soils.*" Atterberg limits tests were conducted in accordance with ASTM D4318-05 "*Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.*" The samples were prepared using the wet method and passed the No.40 sieve. The multi-point method was applied for liquid limit tests.

According to Unified Soil Classification System (USCS) and (AASHTO) classification, soils were classified. Both test results of particle size analysis and Atterberg limits were used for classification.

pH Test

The pH measurement of stabilized and natural subgrade samples was carried out in accordance with ASTM D 4972-01 (2007) "*Standard Test Method for pH of Soils.*" Each 10 g sample was mixed with 10 ml distilled water. Three buffer solutions (pH=4.0, pH=7.0, and pH=12.0) were used for calibration of the meter (Accumet XL20) before testing. After 15 minutes of mixing, the pH of samples was measured.

Unconsolidated-Undrained Triaxial Compression Tests

UU tests were used to determine undrained shear strength followed with ASTM D 2850 "*Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils.*" The tests were conducted using undisturbed Shelby tubes samples of stabilized subgrades. A confining pressure used was 34.5 kPa (5 psi). Figure 12 shows the

Shelby tube sample that was pushed out the tube using a hydraulic piston. Before extruding, all Shelby tubes were stored in a moisture room. The ratio of height to diameter of 2 (142 mm height and 71 mm diameter) was used to prepare test samples. Mass of samples was measured prior to the test and moisture contents were measured after the test to perform volumetric analysis.

Figure 12. Shelby tube sample after extraction

Scanning Electron Microscope Analysis

SEM analysis was used to identify the surface morphology of natural and stabilized subgrade, and compare their differences. The equipments used were a Hitachi S2460-N variable pressure and FEI Quanta 250 FEG scanning electron microscope. Using a blade, the specimens of SEM were prepared with a flat surface (Figure 13). Quantitative mineralogical analysis of subgrade samples was conducted using energy dispersive spectrometry (EDS), which uses the same equipment with SEM. Element maps provide the distribution of elements on the top layer of the sample. The white product was randomly presented in stabilized subgrade at the US 183 test site (Figure 14), which was investigated using SEM.

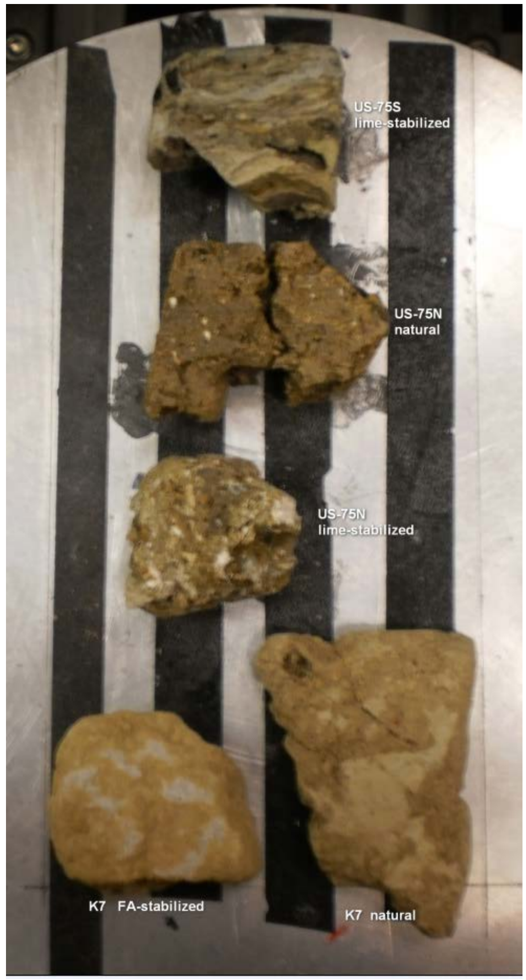


Figure 13. Prepared SEM samples from test sites in Kansas

Figure 14. White product presented in stabilized subgrade at test site of US 183

CHAPTER 4. CASE STUDIES

This chapter consists of site information, material properties, SEM analysis, pH of soil, and in-situ soil strength/stiffness for each test site. The site information describes site location, pavement profile, construction history, and in-situ test point locations. The material properties of soil include soil classification, index properties, and moisture content. The results of pH values of stabilized and natural subgrade are presented. SEM analysis describes soil structure and chemical composition of subgrade. The results of soil strength and stiffness of subgrade are analyzed to evaluate the long-term performance of stabilized subgrade. Site location, section length, layer thickness, stabilizer, and construction year at each site are summarized in Table 6.

Table 6. Summary of test site information

Road Name	Location	Section Length	Current Layer Thickness	Stabilizer	Cons. Year
SH 121	Forth Worth, Tarrant County, TX	370 m	(1) 75 mm AC (2) 200 mm flex base (3) 200 mm stab. subg.	lime	1995
FM 1709	Forth Worth, Tarrant County, TX	300 m	(1) 150 mm AC (2) 200 mm flex base (3) 150 mm stab. subg.	lime	1994
US 287	Mansfield, Tarrant County, TX	600 m	(1) 89 mm AC (2) 280 mm flex base (3) 356 mm stab. subg.	lime	1982
US 183	Clinton, Washita County, OK	300 m	(1) 300 mm AC (2) 203 mm stab. subg.	5% lime	1999
SH 99	Seminole, Seminole County, OK	500 m	(1) 254 mm AC (2) 152 mm base (3) 203 mm stab. subg.	12-14% fly ash	1999
US 59	Clinton, Washita County, OK	500 m	(1) 254 mm AC (2) 254 mm base (3) 203 mm stab. subg.	12-14% fly ash	2000
US 75 SB	Lyndon, Osage County, KS	700 m	(1) 330 mm AC (2) 50 mm base (3) 100 mm stab. subg.	5% lime	1995
US 75 NB	Hoyt, Jackson County, KS	220 m	(1) 229 mm PCC (2) 102 cement treated base (3) 152 mm stab. subg.	lime	1995
K 7	Doniphan, Doniphan County, KS	500 m	(1) 229 mm AC (2) 300 mm stab. subg.	14-18% fly ash	2005

SH 121, TX

Site Description

This project was located on the south bound of SH121 in Fort Worth, Tarrant County, Texas. The general location of this site is shown in Figure 15. This road is a four-lane State Highway. The road was constructed in 1982, and originally consisted of a 25 mm (1 in.) thick asphalt concrete (AC), 200 mm (8 in.) flex base, and 200 mm (8 in.) lime stabilized subgrade. A HMA overlay with a thickness of 50 mm (2 in.) was placed in 2008. The current pavement consists of a 75 mm (3 in.) thick asphalt concrete (AC), a 200 mm (8 in.) flex base, and 200 mm (8 in.) lime stabilized subgrade. The length of this test section is approximately 370 m (1214 ft). Iowa State University (ISU) research team conducted in-situ testing on August 4, 2010 with assistance and traffic control provided by Texas DOT.

The plan view of in-situ test locations is shown in Figure 16. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 10-30 m from test points 1 to 14. DCP were conducted at test point 4. After coring, LWD was performed on the top of stabilized subgrade at test points 4, 7, and 11. PLT was performed on the top of stabilized subgrade at test points 4 and 7. Bag samples of base and stabilized subgrade were collected at test points 4, 7, and 11.

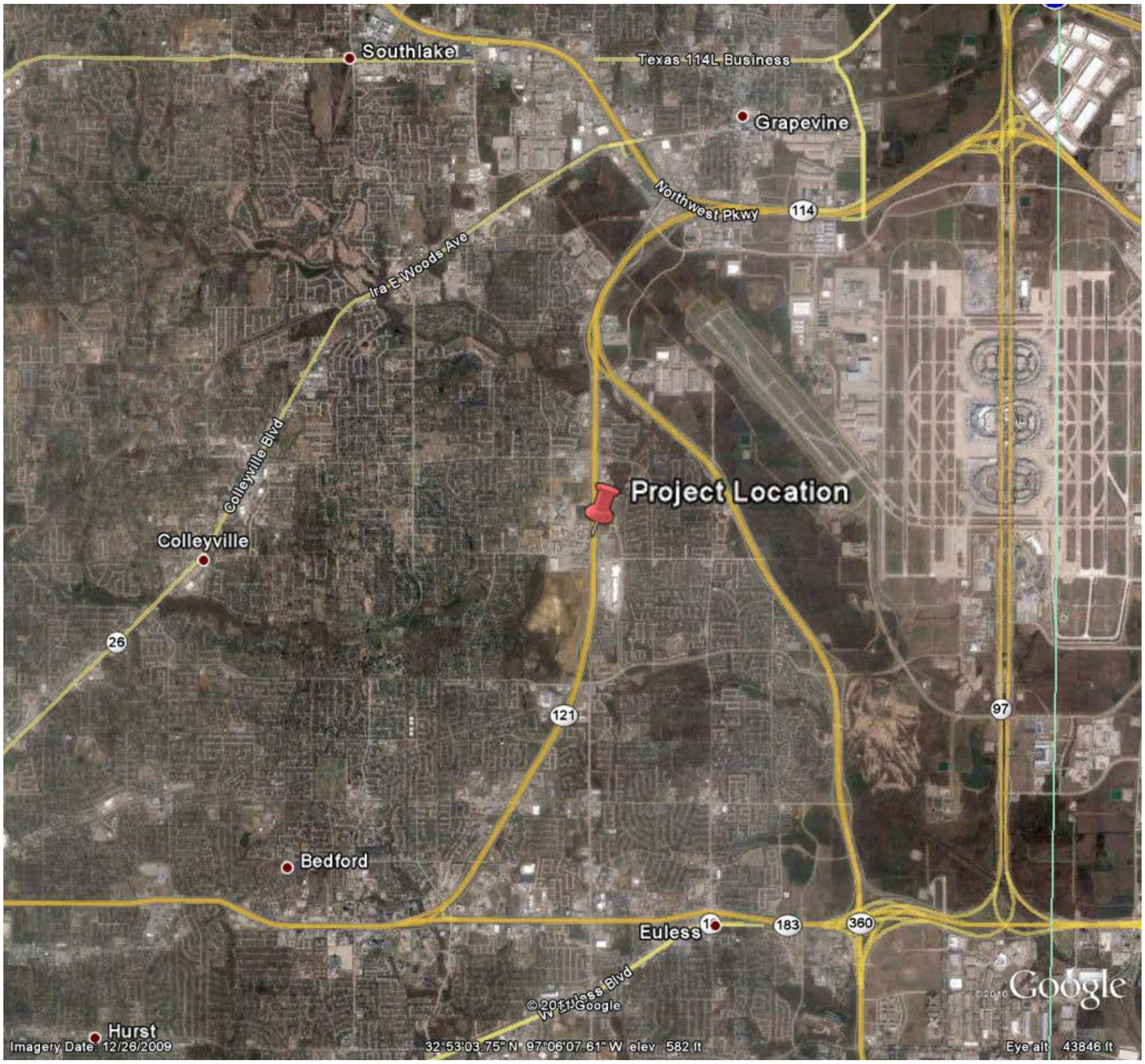


Figure 15. Project location of SH 121

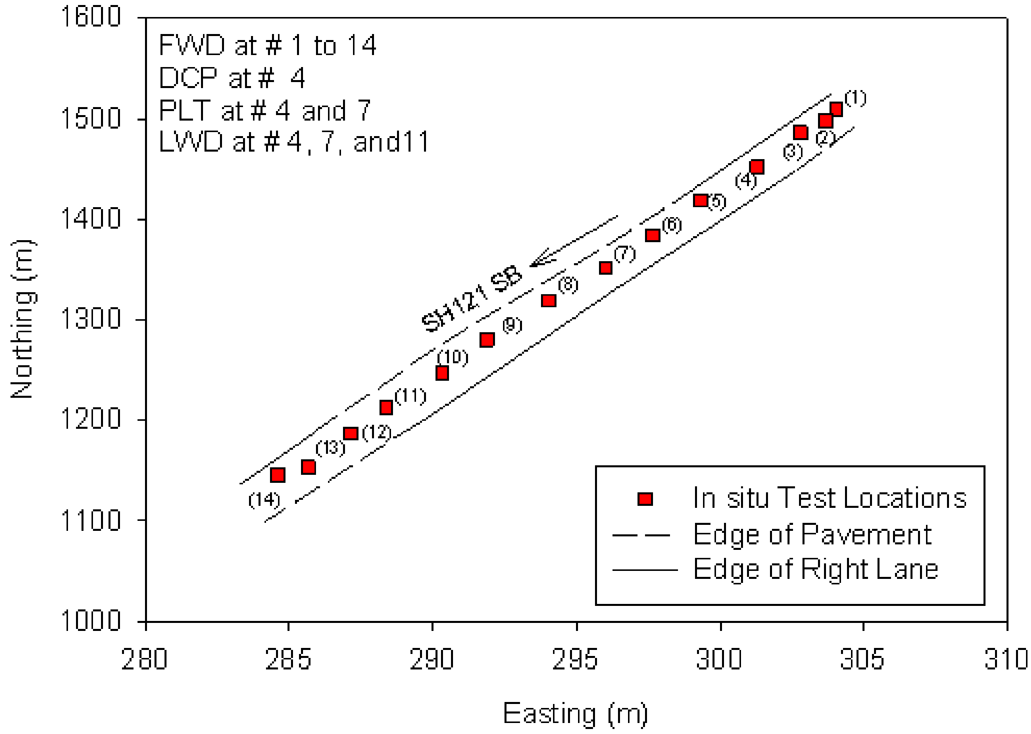


Figure 16. Test section plan layout

Figure 17. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The base and stabilized subgrade samples were taken at test point 7. According to USCS and AASHTO, the flex base was classified as GM and A-1-b, and the stabilized subgrade was classified as SM and A-2-4. Table 7 presents material properties of base and subgrade. The sand content of stabilized subgrade was high about 62.4%, and the clay content was low about 6.7%. The LL value of stabilized subgrade sample was 26.5. The stabilized subgrade is a non plastic soil. Figure 18 shows particle size distribution curves of base and stabilized subgrade.

Table 7. Summary of material properties

Parameter	**SH 121 TX**	
Material Description	Base	Stabilized Subgrade
Depth mm (in.)	0-200 (0-8)	0-100 (0-4)
Gravel Content (%) (> 4.75mm)	46.3	10.2
Sand Content (%) (4.75mm – 75μm)	37.2	62.4
Silt Content (%) (75μm – 2μm)	12.9	20.7
Clay Content (%) (< 2μm)	3.6	6.7
Coefficient of Uniformity (C_u)	501.8	40.6
Coefficient of Curvature (C_c)	6.3	5.8
Liquid Limit, LL (%)	21.0	26.5
Plasticity Index, PI	9.0	N.P.
AASHTO	A-1-b	A-2-4
USCS	GM	SM
Water Content (%)	3.9	15.4

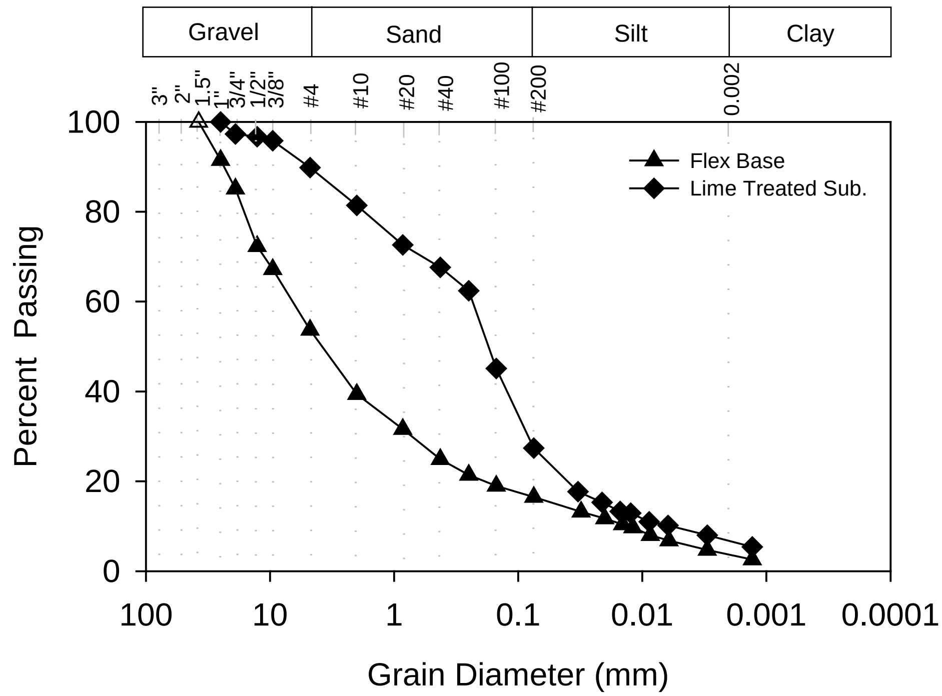


Figure 18. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

The pH value of stabilized subgrade was 9.2.

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 19. The majority elements were silica (Si), alumina (Al), and oxygen (O). Calcium (Ca) is rarely presented in this sample. Additional present elements were iron (Fe) and magnesium (Mg).

Figure 20 and Figure 21 compares element concentration with different magnification in Al, Si, O, S, Mg, Ca, K, and C for stabilized subgrade. The sample at 30 × magnifications shows higher concentration of Ca than that sample at 150 × magnifications. The sample at 500× magnification shows higher concentration of Al, O, and Si than the sample at 150× magnification. All SEM images are presented in Figure 22 and Appendix D.

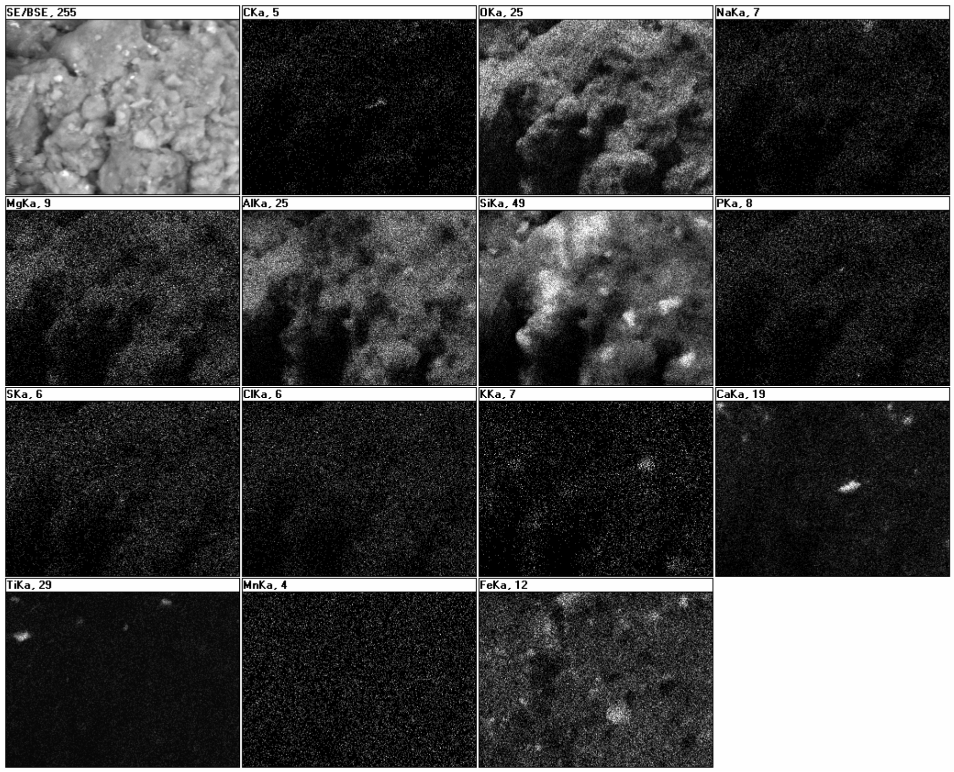


Figure 19. EDS map of stabilized subgrade sample (1500×)

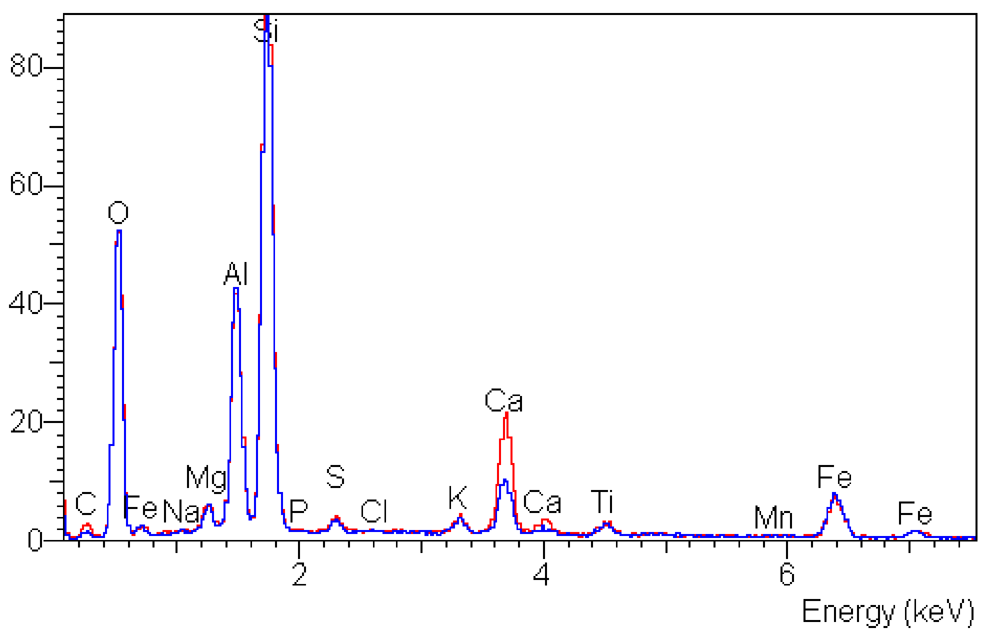


Figure 20. EDS intensity counts for stabilized subgrade sample (red line: 30×; blue line: 150×)

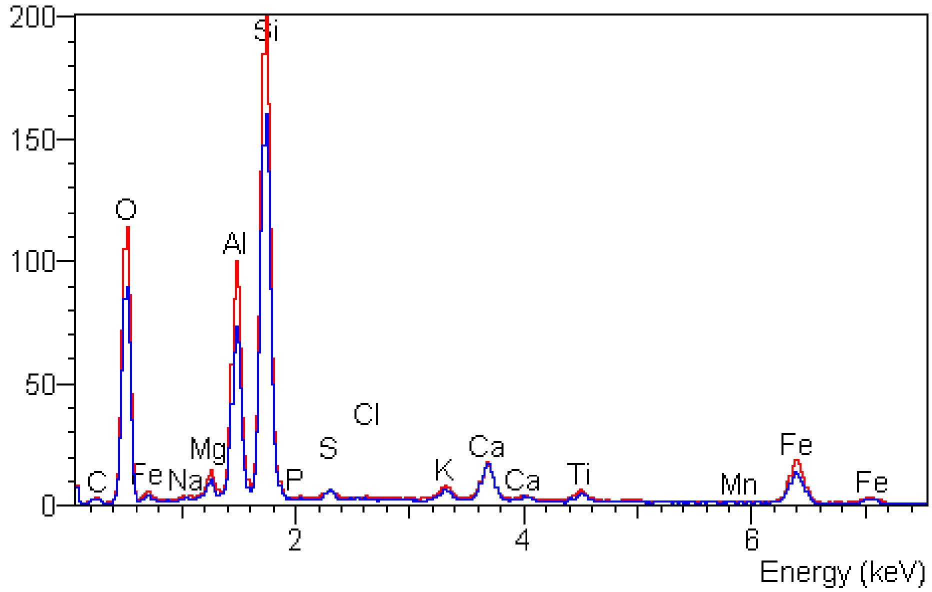


Figure 21. EDS intensity counts for stabilized subgrade sample (red line: 500× magnification, blue line: 150× magnification)

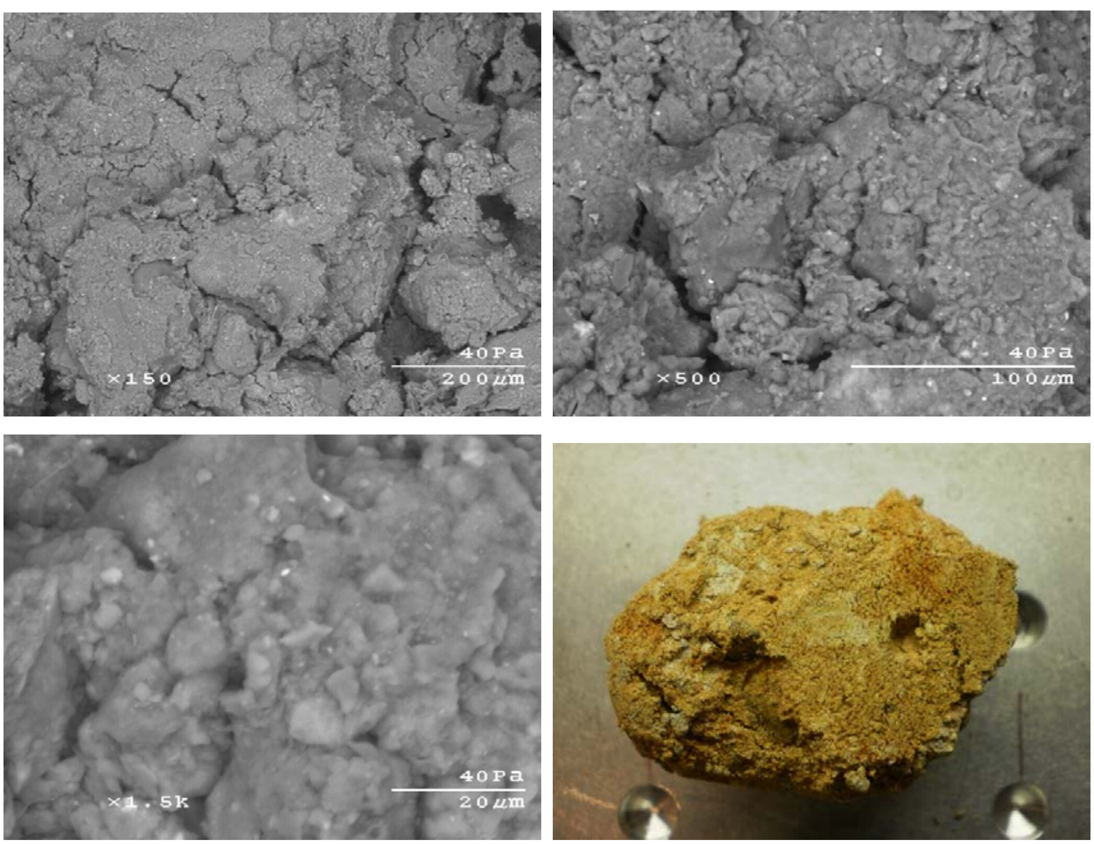


Figure 22. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP-CBR profile is shown in Figure 23. The major observations are: (1) the average CBR of the stabilized subgrade was 95%, (2) the average CBR increases as the depth increases, and (3) the top 50 mm (2 in.) stabilized subgrade has a low CBR ranging from 8-20%.

Backcalculated subgrade elastic moduli (E_{FWD}) and deflections (D_0) were presented in Figure 24. In the backcalculation, the applied test load was 57.7 KN (12965 lb). The assumptions of poison's ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, flex base, stabilized subgrade, and natural subgrade layer respectively. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The key findings are:

- The average D_0 was about 0.32 mm under the applied average load. As D_0 decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 262 MPa for natural subgrade and increased to 1129 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 430% of natural subgrade
- The values of E_{FWD} of stabilized and natural subgrade varied significantly indicating non-uniform subgrade properties.

Figure 25 presents the stress-strain relationship at test points 4 and 7. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 26 and Figure 27. The correction of k′u was made using the curve in Figure 8. The average LWD elastic modulus (E_{LWD}) was presented in Table 8. The average E_{LWD} of stabilized subgrade was equal to 0.4 E_{V1} and 0.2 E_{V2}. The elastic modulus ratio between stabilized and natural subgrade is provided in Table 9. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 10. All in-situ test results are presented in Appendix F.

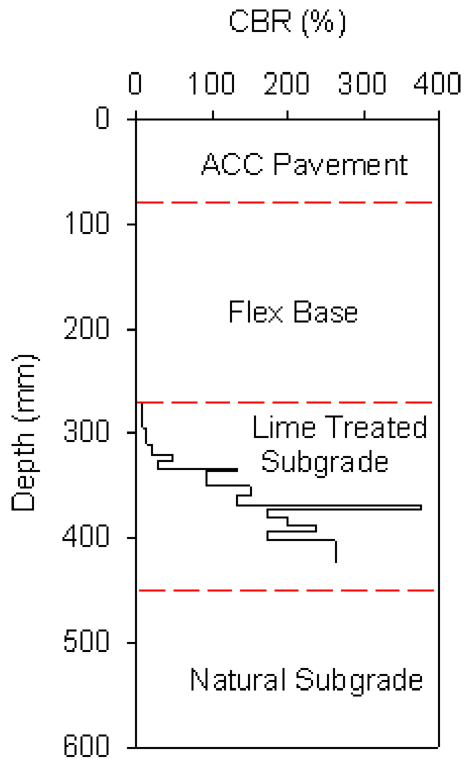


Figure 23. CBR – DCP profile at test point 4

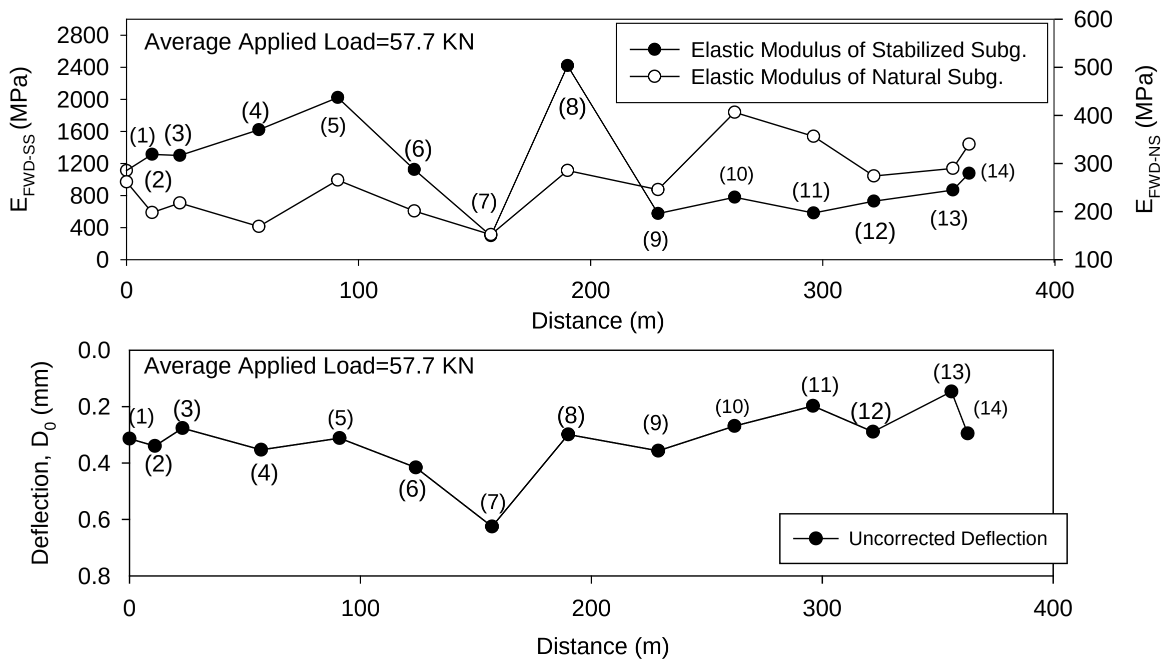


Figure 24. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

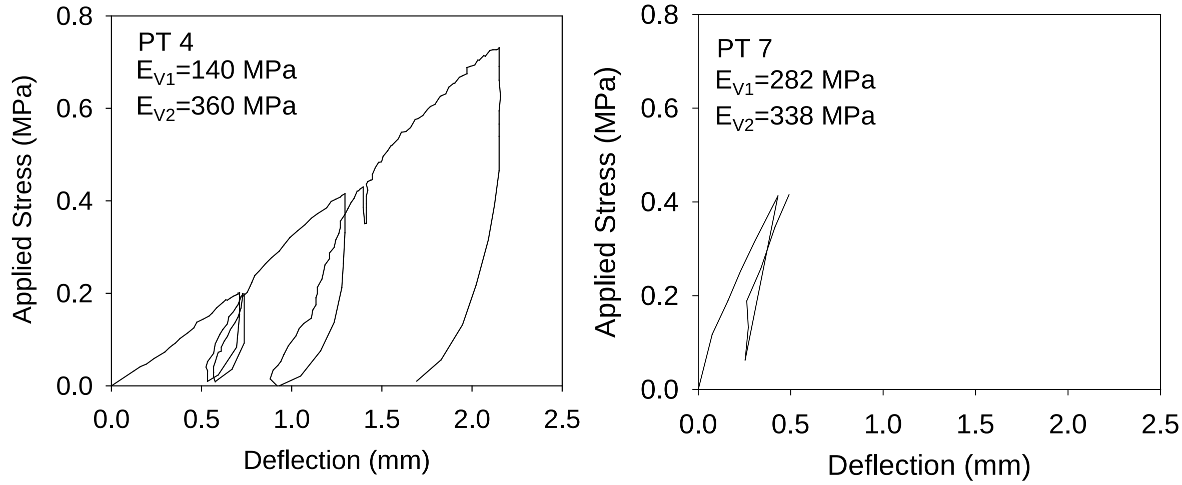


Figure 25. Stress – strain curves from plate load tests at points 4 and 7

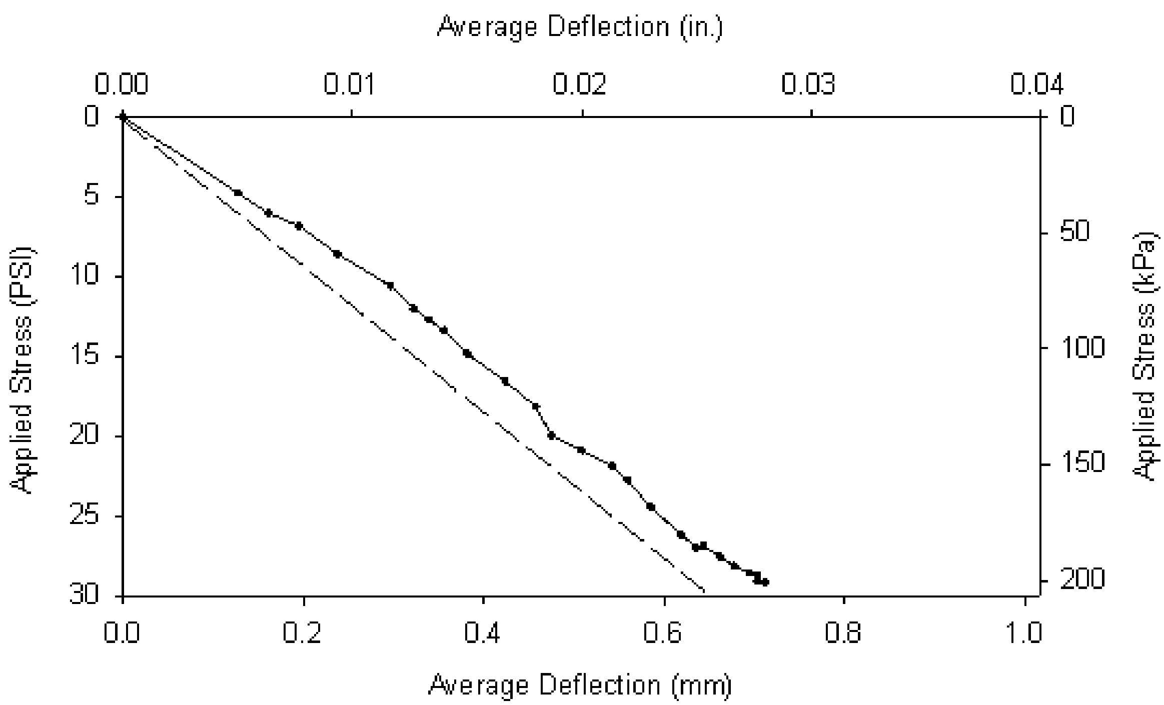


Figure 26. Stress – strain curves for obtaining K_U at point 4

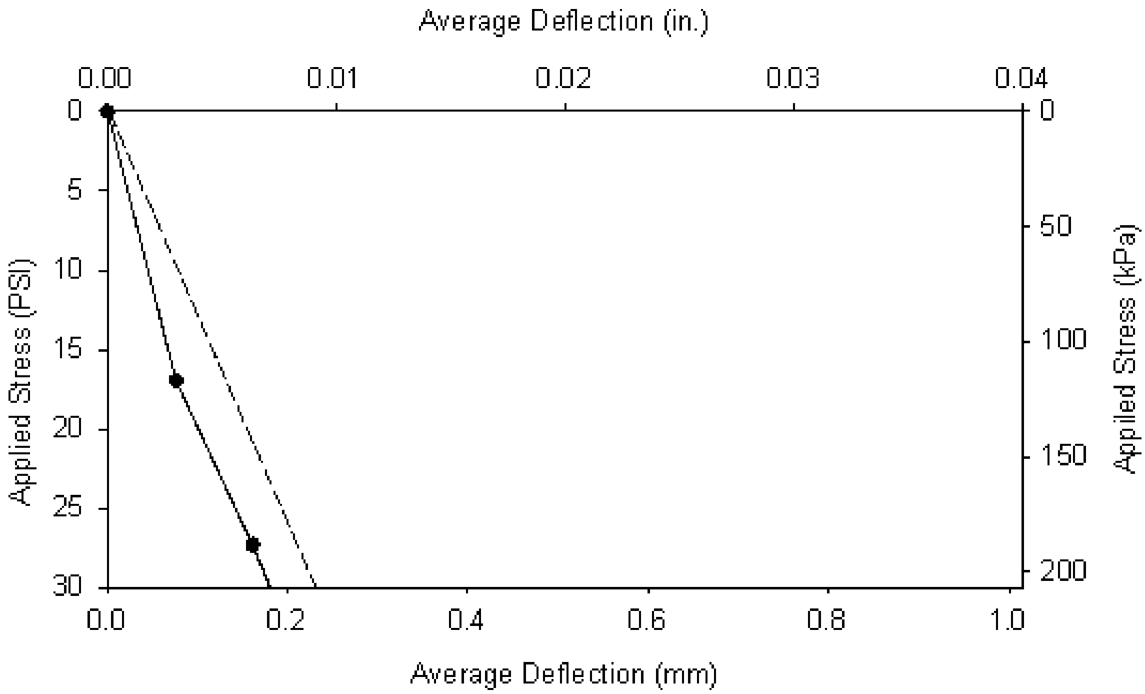


Figure 27. Stress – strain curves for obtaining Kuat at point 8

Table 8. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Ave. E_{LWD}
			MPa	MPa
PT 4	Base	Top of base	93	108
PT 11	Base	25 mm from top of base	125	
PT 4	Base	75 mm from top of base	73	
PT 7	Base	100 mm from top of base	140	
PT 4	Stab. subgrade	Top of stab. subgrade	51	69
PT7	Stab. subgrade	Top of stab. subgrade	87	
PT 11	Stab. subgrade	Top of stab. subgrade	70	

Table 9. Summary of elastic modulus ratio between stabilized and natural subgrade

Ratio of Stab. Subg./Nat. Subg.	
E_{FWD}	4.3

Table 10. Summary statistics of test results from in-situ testing

Statistic	Flex Base	Stabilized Subgrade						Nat. Subg.	FWD Def.
Measurement	E_{LWD}	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	E_{FWD}	$D_{0\text{-Cor.}}$
	MPa	%	MPa	MPa	MPa	MPa	kPa/mm	MPa	mm
Number of Measurement (n)	4	1	14	3	2	2	2	14	14
Mean Value (μ)	108	119	1129	69	211	349	182	262	0.32
Standard Deviation (σ)	30	—	583	18	100	16	—	72	0.11
Coefficient of Variation COV(%)	28	—	52	26	48	4	—	28	33

FM 1709, TX

Site Description

This project was located on the west bound of FM 1709 in Fort Worth, Tarrant County, Texas. The general location of this site is shown in Figure 28. This road is a six-lane Urban Road. The old pavement was constructed in 1987, and originally consisted of a 100 mm (4 in.) thick asphalt concrete (AC), a 200 mm (8 in.) flex base, and 150 mm (6 in.) lime stabilized subgrade. A 50 mm (2 in.) HMA overlay was placed in 2007. The pavement currently consists of a 150 mm (6 in.) thick asphalt concrete (AC), 200 mm (8 in.) flex base, and 150 mm (6 in.) lime stabilized subgrade. The length of this test section is approximately 300 m (984 ft). ISU research team conducted in-situ testing on August 4, 2010 with assistance and traffic control provided by Texas DOT.

The plan view of in-situ test locations is shown in Figure 29. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 40 m from test points 1 to 7. DCP were conducted at test point 1. After coring, LWD and PLT were only performed on the top of stabilized subgrade at test point 1. Bag samples of base and stabilized subgrade were collected at test point 1.

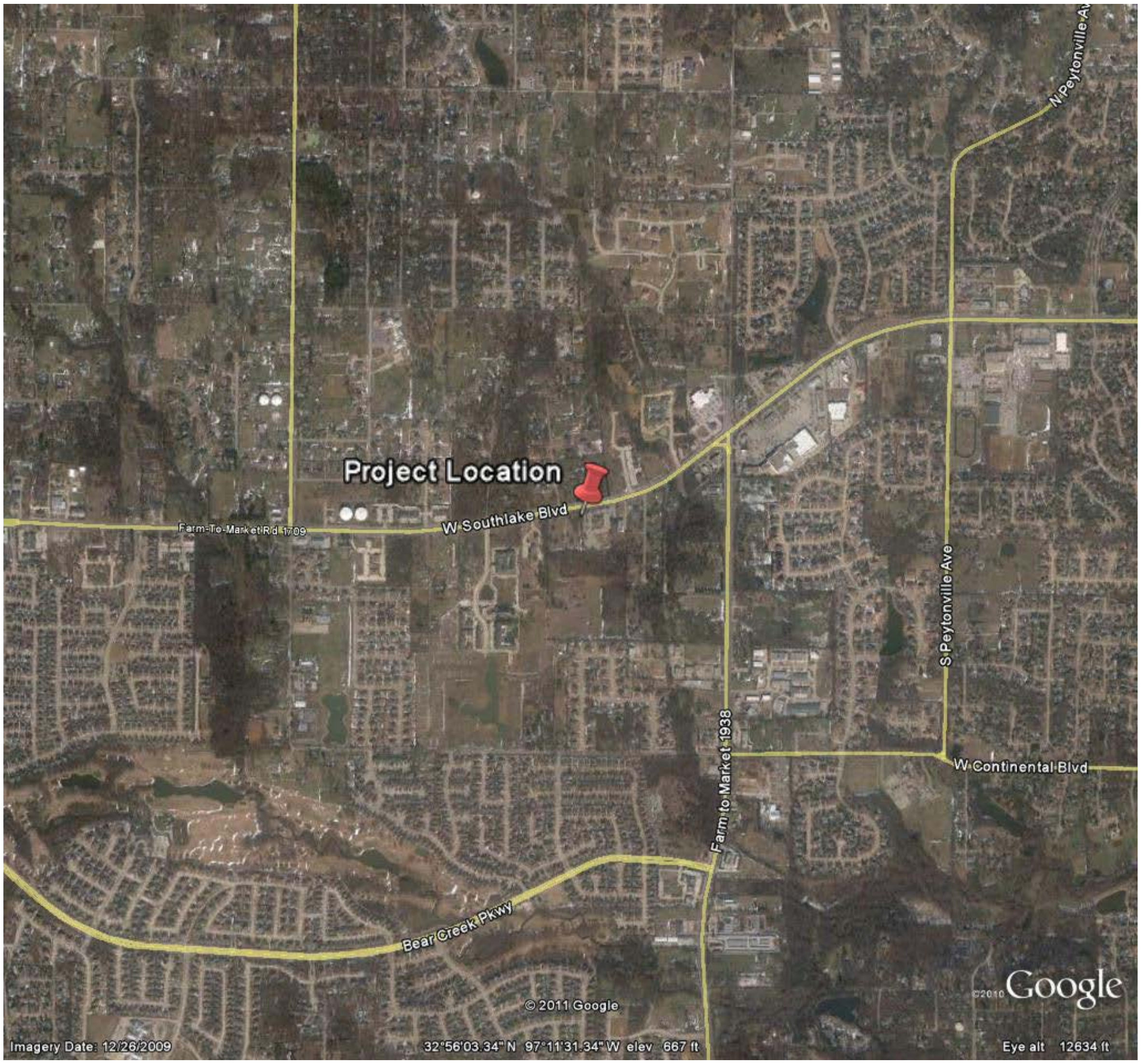


Figure 28. Project location of FM 1709

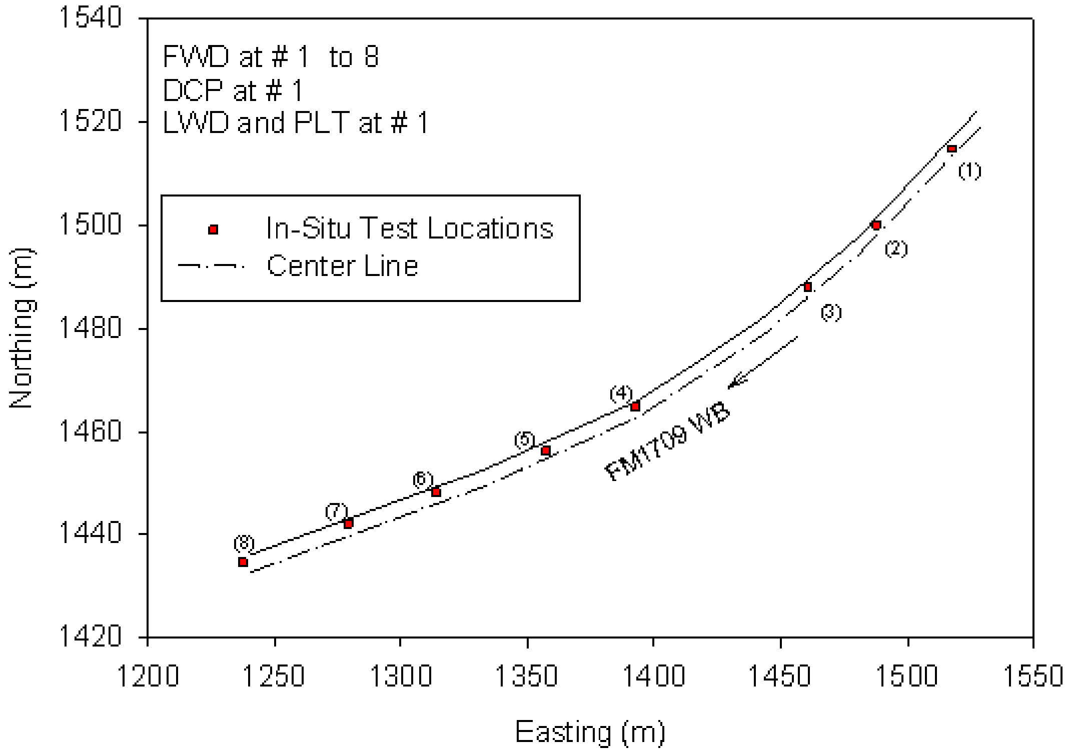


Figure 29. Test section plan layout

Figure 30. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The base and stabilized subgrade samples were taken at test point 1. According to USCS and AASHTO, the flexible base was classified as GM and A-1-b, and the stabilized subgrade was classified as SM and A-4. Table 11 provides material properties of subgrade, and it is shown that gravel, sand, silt, and clay content of soil sample. The stabilized subgrade is a non plastic soil. Figure 31 shows particle size distribution curves of base and subgrade.

Table 11. Summary of material properties

Parameter	**FM 1709 TX**	
Material Description	Base	Stabilized Subgrade
Depth mm (in.)	0-200 (0-8)	0-75 (0-3)
Gravel Content (%) (> 4.75mm)	42.8	4.2
Sand Content (%) (4.75mm – 75μm)	37.1	55.2
Silt Content (%) (75μm – 2μm)	15.4	36.9
Clay Content (%) (< 2μm)	4.7	3.7
Coefficient of Uniformity (C_u)	856.4	14.1
Coefficient of Curvature (C_c)	10.0	2.2
Liquid Limit, LL (%)	21.2	—
Plasticity Index, PI	7.5	N.P.
AASHTO	A-1-b	A-4
USCS	GM	SM
Water Content (%)	7.0	17.3

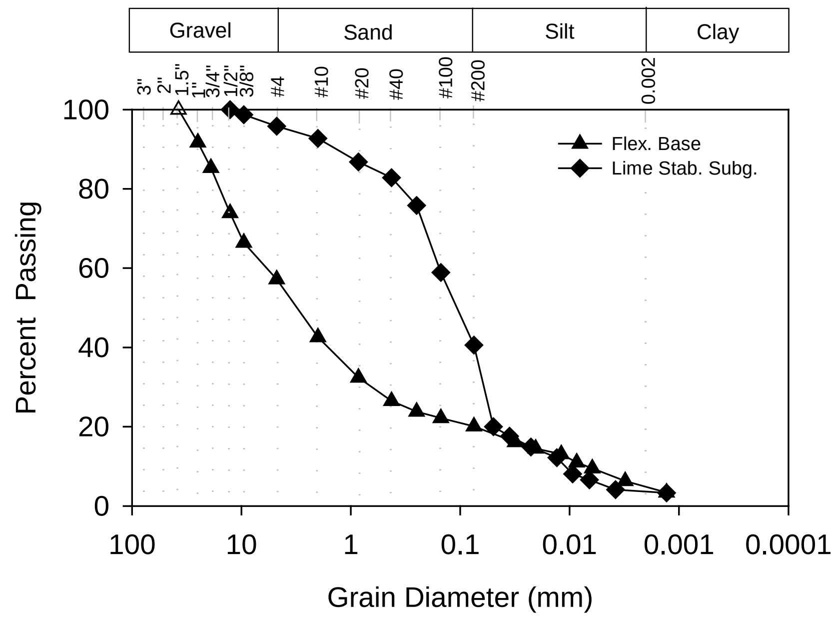


Figure 31. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

The pH value of stabilized sample was 9.6.

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 32 and Figure 33. The majority elements were calcium (Ca), silica (Si), alumina (Al), and oxygen (O). These elements commonly exist in lime stabilized subgrade. Additional elements were iron (Fe), potassium (K), and Sodium (Na).

Figure 34 shows element concentration in Al, Si, O, S, Mg, Ca, K, and C for stabilized subgrade. The stabilized subgrade sample has higher concentration of Si, Al, O, and Ca, and less concentration of C, Fe, and Mg. All SEM images are presented in Figure 35 and Appendix D.

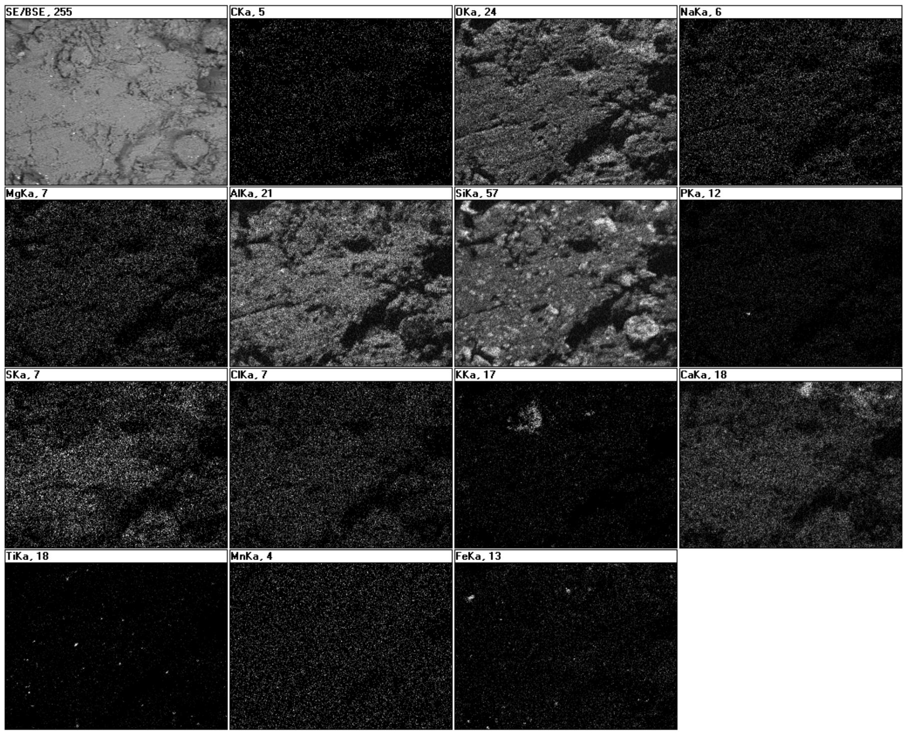


Figure 32. EDS map of stabilized subgrade sample (150 ×)

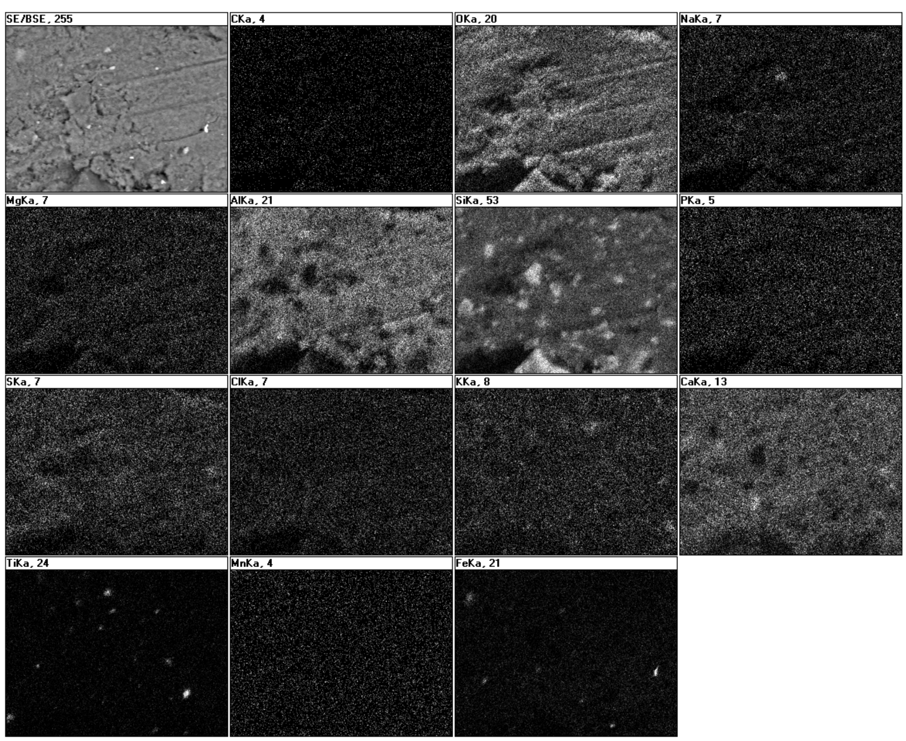


Figure 33. EDS map of stabilized subgrade sample (800 ×)

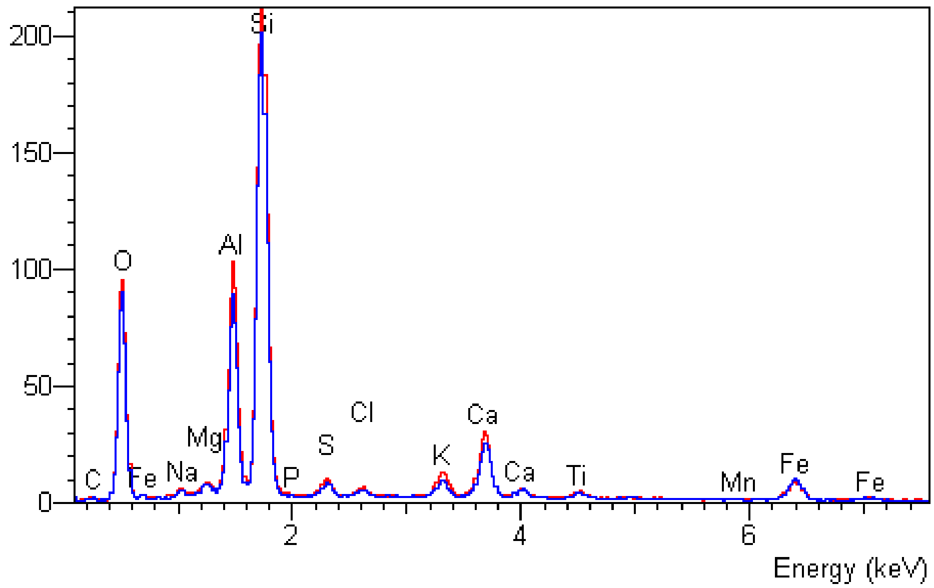


Figure 34. EDS intensity counts for stabilized subgrade sample (red line: 500×; blue line: 150×)

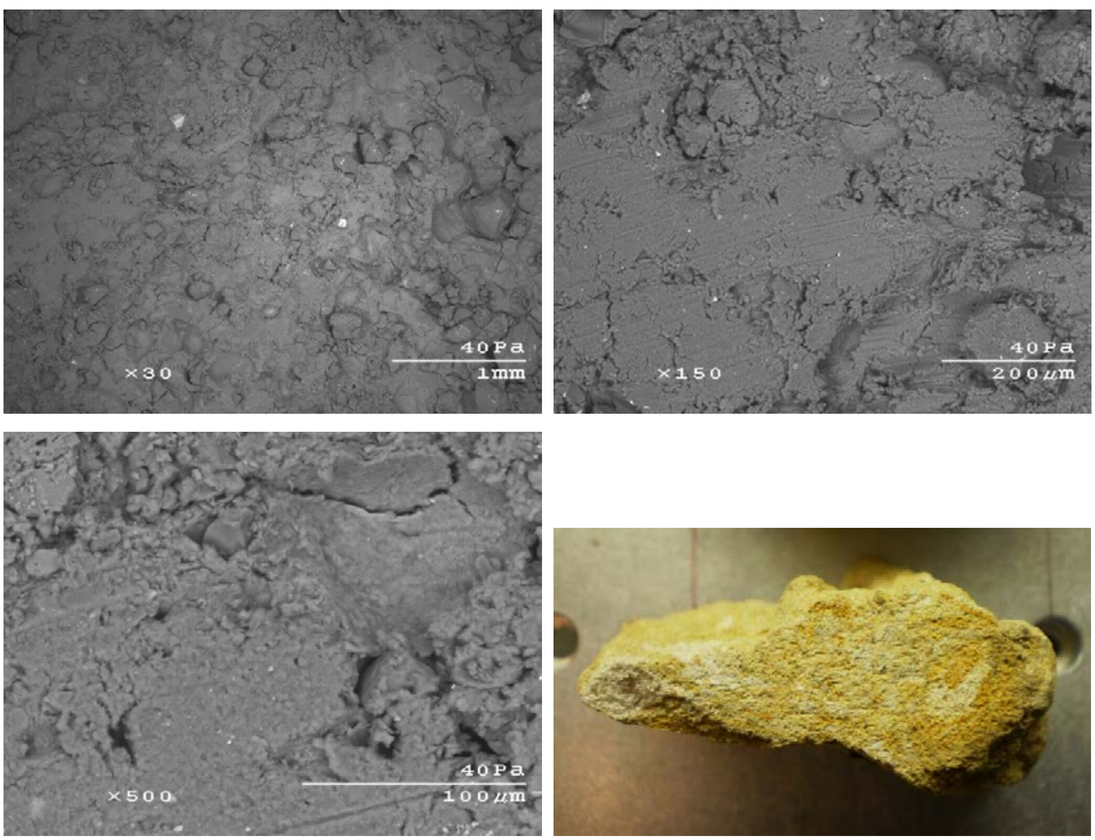


Figure 35. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP-CBR profile and cumulative drops versus CBR are shown in Figure 36. The following observations are: (1) the average CBR of the stabilized subgrade was 53%, (2) the average CBR of the natural subgrade was 24%, (3) the CBR of the stabilized subgrade was 220% of the natural subgrade, and (4) the top 50 mm (2 in.) layer of stabilized subgrade has very low CBR ranging from 10-30%.

Backcalculated subgrade elastic moduli (E_{FWD}) and deflections (D_0) were presented in Figure 37. In the backcalculation, the applied test load was 56.0 KN (12573 lb). The assumptions of poison's ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, flex base, stabilized subgrade, and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The key findings are:

- The average D_0 was about 0.45 mm under the applied average load. As D_0 decreases, backcalculated E_{FWD} of stabilized and natural subgrade increase.
- The average E_{FWD} was 127 MPa for natural subgrade and increased to 396 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 310% of natural subgrade
- For those test points, the values of E_{FWD} of stabilized and natural subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 38 presents the stress-strain relationship at test point 1. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 39. The correction of k′u was made using the curve in Figure 8. The average LWD elastic modulus (E_{LWD}) of stabilized subgrade was equal to 1.4 E_{V1} and 1.0 E_{V2}.

Table 12 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 13. All in-situ test results are presented in Appendix F.

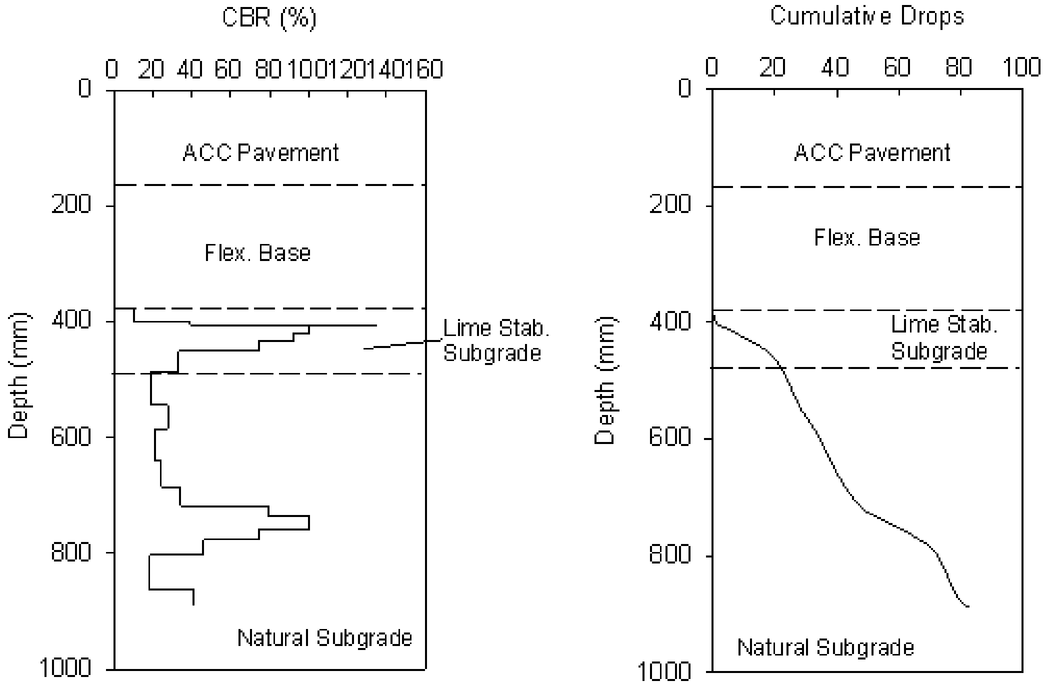


Figure 36. CBR – DCP profile and cumulative drops versus CBR at test point 1

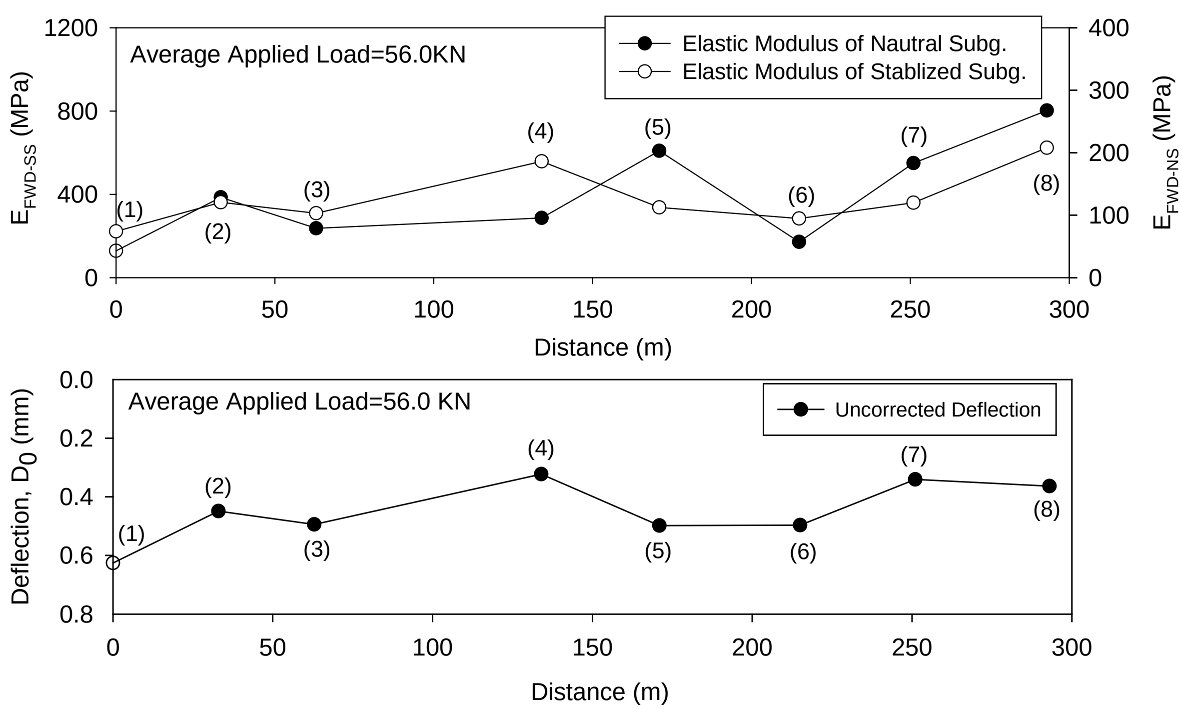


Figure 37. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

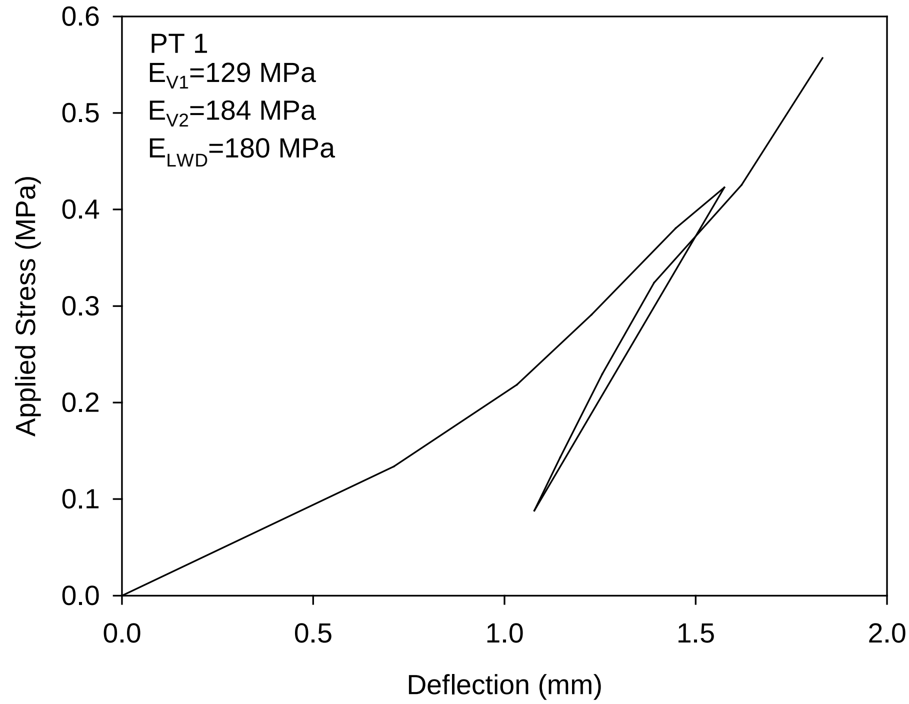


Figure 38. Corrected stress – strain curve from plate load test at point 1

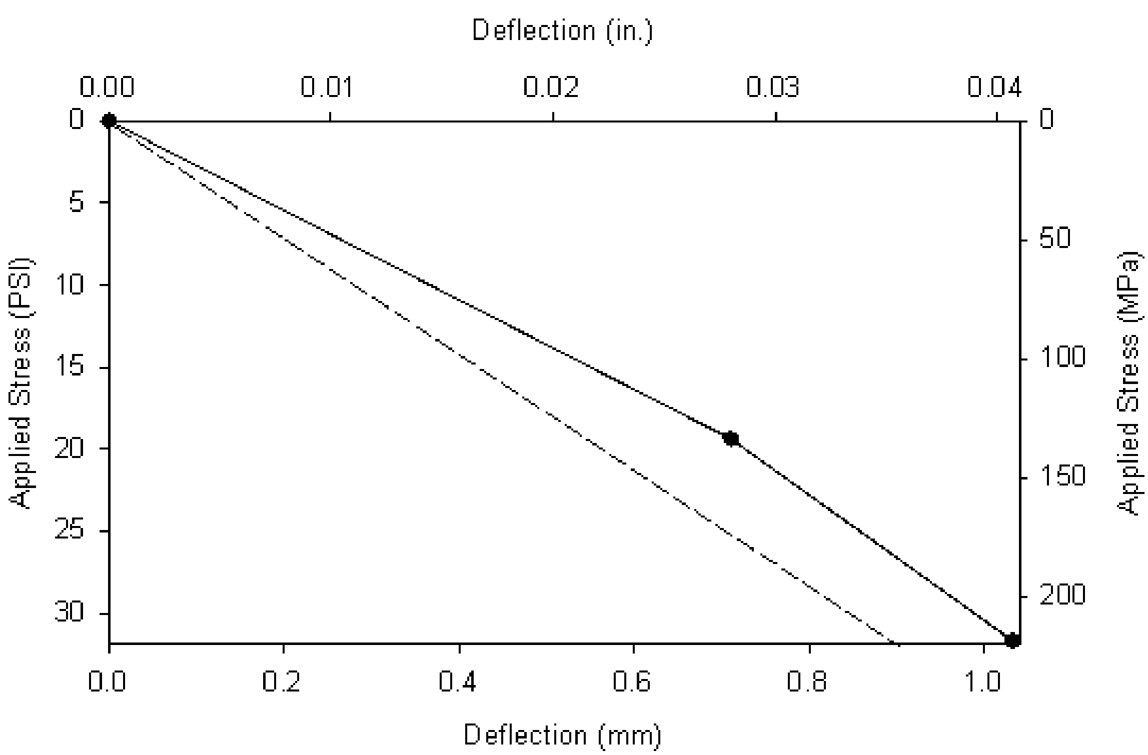


Figure 39. Stress – strain curves for obtaining K_U at point 1

Table 12. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio	
CBR	E_{FWD}
2.2	3.1

Table 13. Summary statistics of test results from in-situ testing

Statistic	Stabilized Subgrade							Natural Subgrade		FWD Def.
Measurement	CBR	E_{LWD}	E_{V1}	E_{V2}	E_{FWD}	k_U	Thi.	CBR	E_{FWD}	D_0
	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	mm
Number of Measurement (n)	1	1	1	1	8	1	1	1	8	8
Mean Value (μ)	53	180	129	184	396	99	100	24	127	0.45
Standard Deviation (σ)	—	—	—	—	237	—	—	—	46	0.10
Coefficient of Variation COV (%)	—	—	—	—	60	—	—	—	36	23

US 287, TX

Site Description

This project was located on the south bound of US 287 in Mansfield, Tarrant County, Texas. The general location of this site is shown in Figure 40. The road is a four-lane U.S. Highway. The old pavement was constructed in 1982, and originally consisted of a 38 mm (1.5 in.) thick asphalt concrete (AC), 280 mm (11 in.) flex base, and 356 mm (14 in.) lime stabilized subgrade. A HMA overlay with a thickness of 50 mm (2 in.) was placed in 2008. The pavement currently consists of a 89 mm (3.5 in.) thick asphalt concrete (AC), 280 mm (11 in.) flex base, and 356 mm (14 in.) lime stabilized subgrade. The length of this test section is approximately 600 m (1969 ft). ISU research team conducted in-situ testing on August 5, 2010 with assistance and traffic control provided by Texas DOT.

The plan view of in-situ test locations is shown in Figure 41. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 20-30 m from test points 1 to 19. DCP were conducted at test points 12, 15, and 16. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 12. Bag samples of base and stabilized subgrade were collected at test point 12.

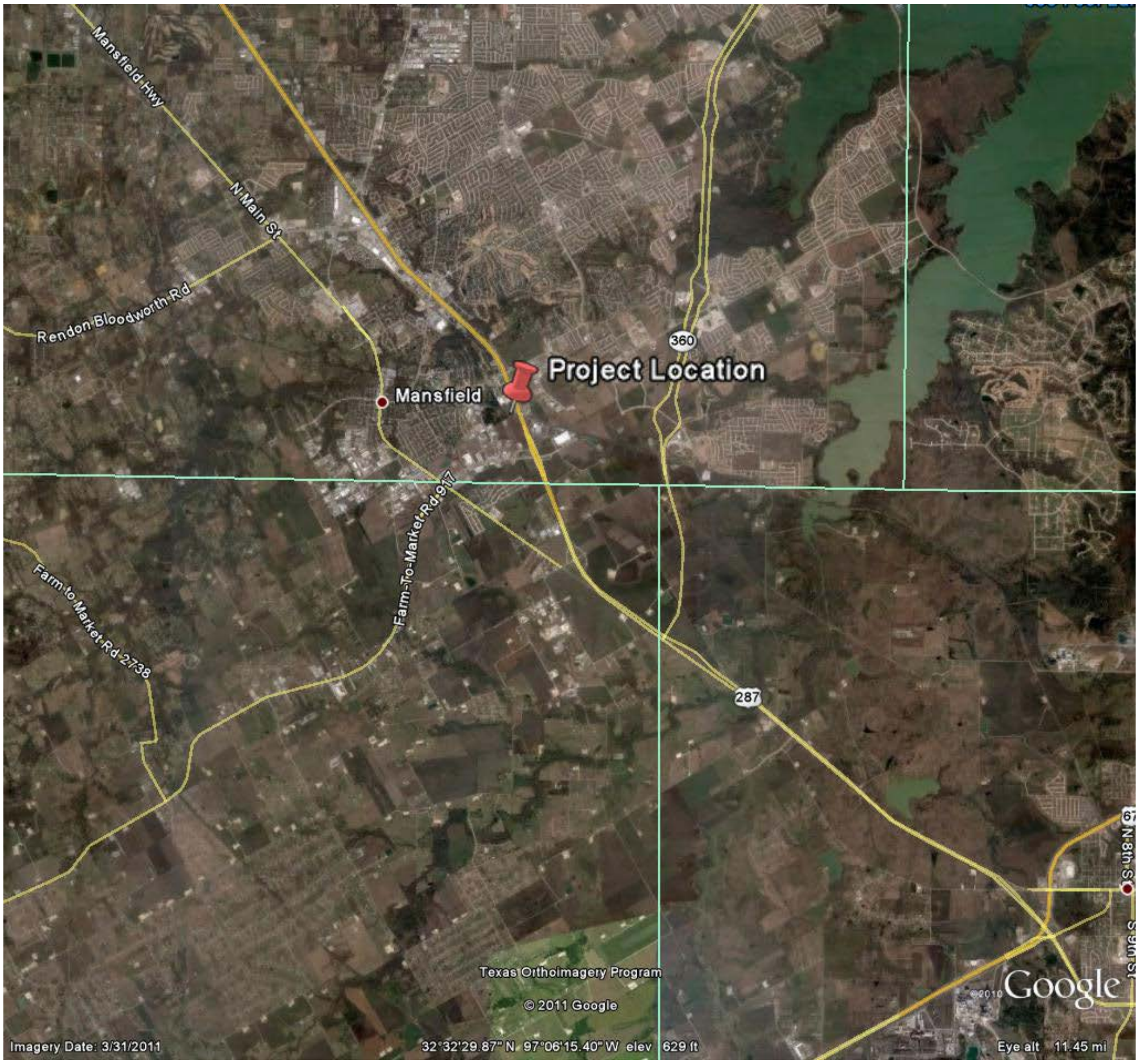


Figure 40. Project location of US 287

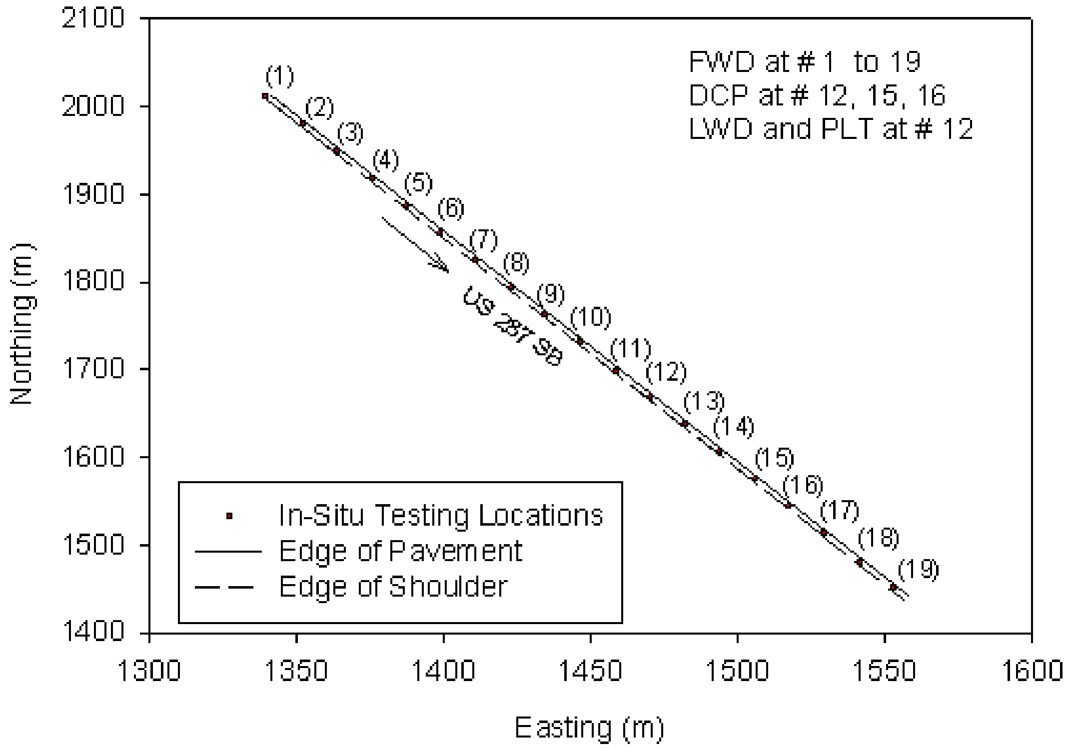


Figure 41. Test section plan layout

Figure 42. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The base and stabilized subgrade samples were taken from different depths at test point 12 from the top to a depth of 200 mm (8 in.). According to USCS and AASHTO, the top 50 mm (2 in.) stabilized subgrade was classified as ML and A-4, and the stabilized subgrade from a depth of 50-200 mm (2-8 in.) was classified as SM and A-4. It is noticed that the top 50 mm (2 in.) stabilized soil shows different soil type with the stabilized subgrade from a depth of 50-200 mm (2-8 in.). Table 14 provides material properties of base and stabilized subgrade. The average PI value of the top 50 mm (2 in.) stabilized subgrade samples is higher than the stabilized subgrade from a depth of 50-200 mm (2-8 in.). Figure 43 shows particle size distribution curves of base and subgrade materials at varied depths. Test results show the soil type of subgrade has been modified after treatment.

Table 14. Summary of material properties

Parameter	**US 287 TX**			
Material Description	Base	Stab. Subgrade	Stab. Subgrade	Stab. Subgrade
Depth mm (in.)	0-280 (0-11)	0-50 (0-2)	50-150 (2-6)	150-200 (6-8)
Gravel Content (%) (> 4.75mm)	51.1	6.4	2.6	17.2
Sand Content (%) (4.75mm – 75µm)	32.6	36.7	56.8	47.1
Silt Content (%) (75µm – 2µm)	11.8	31.6	26.9	29
Clay Content (%) (< 2µm)	4.5	25.3	13.7	6.7
Coefficient of Uniformity (C_u)	692.7	286	346.8	262.1
Coefficient of Curvature (C_c)	17.0	0.21	0.22	1.24
Liquid Limit, LL (%)	17.0	54.8	54.4	54.6
Plasticity Index, PI	6.6	20.0	12.9	13.4
AASHTO	A-1-b	A-4	A-4	A-4
USCS	GM	ML	SM	SM
Water Content (%)	6.5	33.3	35.4	36.7

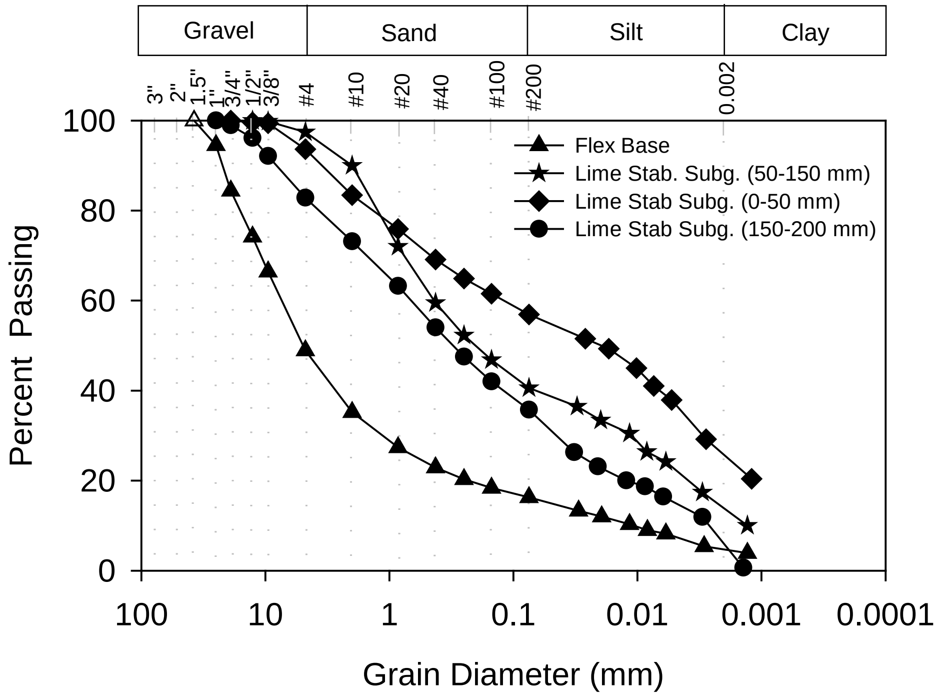


Figure 43. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Table 15 shows pH values of stabilized subgrade from a depth of 0-200 mm (0-8 in.). It decreases gradually from the top to bottom of stabilized subgrade.

Table 15. Summary of pH value of subgrade

Depth mm (in.)	**pH**
0-50 (0-2)	8.2
50-150 (2-6)	8.7
150-200 (6-8)	9.2

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 44. The majority elements were calcium (Ca), silica (Si), alumina (Al), and oxygen (O). These elements commonly exist in lime stabilized subgrade. Additional elements were iron (Fe), potassium (K), and Sodium (Na).

Figure 45 and Figure 46 compares element concentration in Al, Si, O, S, Mg, Ca, K, and C for stabilized subgrade. The sample shows higher concentration of Ca, Si, Al, and O, and less concentration of Fe, S, and Mg. All SEM images are presented in Figure 47 and Appendix D.

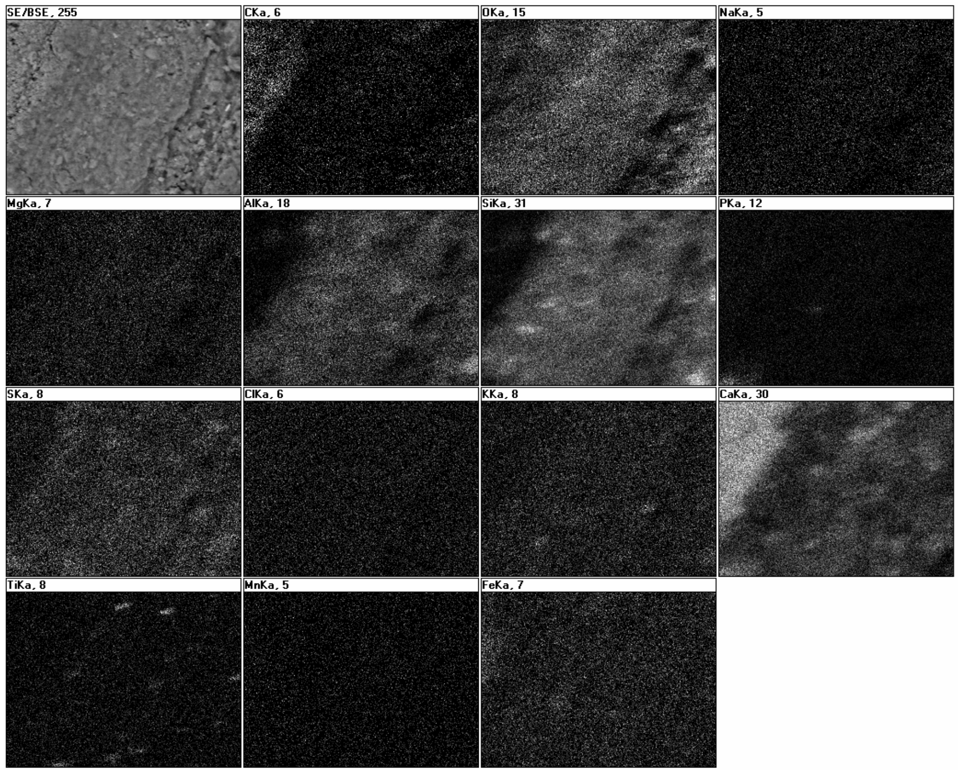


Figure 44. EDS map of stabilized subgrade sample (1000 × magnification)

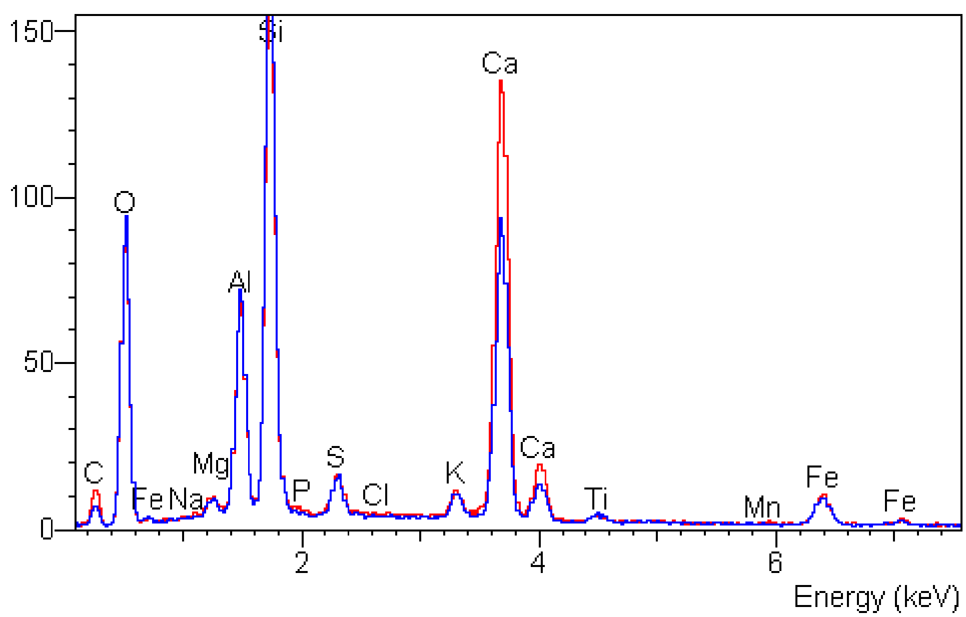


Figure 45. EDS intensity counts for stabilized subgrade sample (red line: 500×; blue line: 150×)

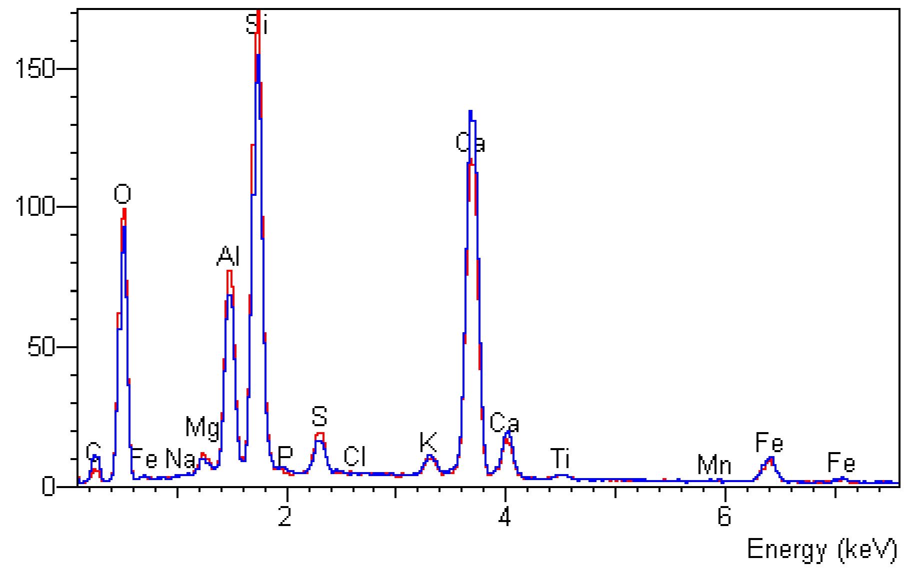


Figure 46. EDS intensity counts for stabilized subgrade sample (red line: 1000×; blue line: 500×)

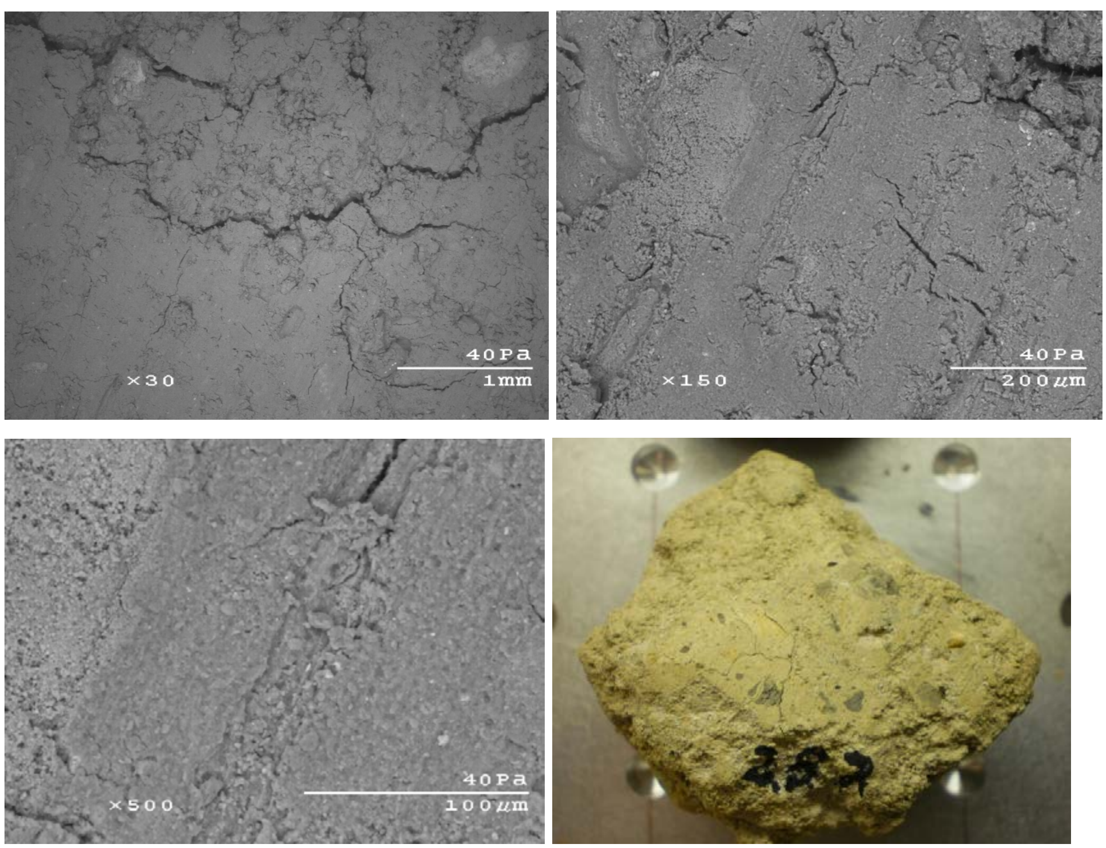


Figure 47. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP-CBR profile and cumulative drops versus CBR are shown in Figure 48. The major observations are: (1) the average CBR of the stabilized subgrade was 163%, (2) the average CBR of the natural subgrade was 22%, (3) the CBR of the stabilized subgrade was 740% of the natural subgrade, (4) the top and bottom layer of stabilized subgrade has a lower CBR than the middle layer, and (5) from DCP profiles, the actual treatment thickness was thicker than the design value.

Backcalculated subgrade elastic moduli (E_{FWD}) and deflections (D_0) were presented in Figure 49. In the backcalculation, the applied test load was 57.0 KN (12785 lb). The assumptions of poison's ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, flex base, stabilized subgrade, and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The key findings are:

- The average D_0 was about 0.34 mm under the applied average load. As D_0 decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 111 MPa for natural subgrade and increased to 926 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was 830% of the natural subgrade.
- The values of E_{FWD} of natural and stabilized subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 50 presents the stress-strain relationship at test point 12. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 51. The correction of k′u was made using the curve in Figure 8. The average LWD elastic modulus (E_{LWD}) of stabilized subgrade was presented in Table 16, which is equal to 0.4 E_{V1} and 0.3 E_{V2}. Table 17 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 18. All in-situ test results are presented in Appendix F.

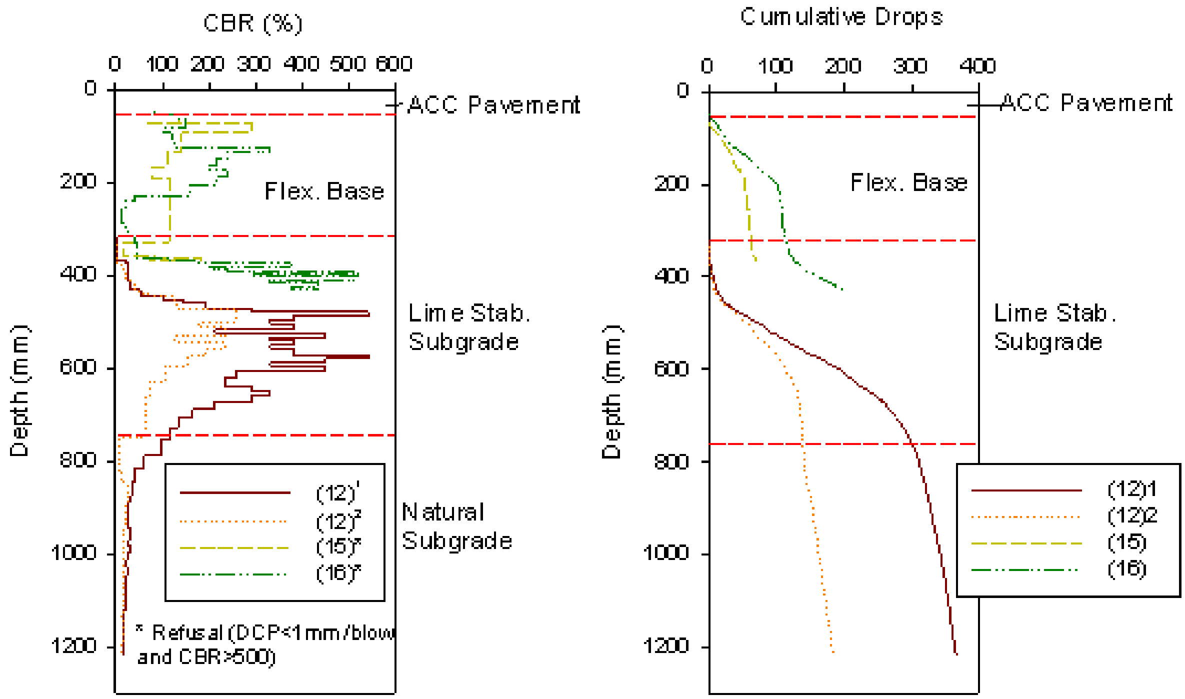


Figure 48. CBR – DCP profile and cumulative drops versus CBR of test points

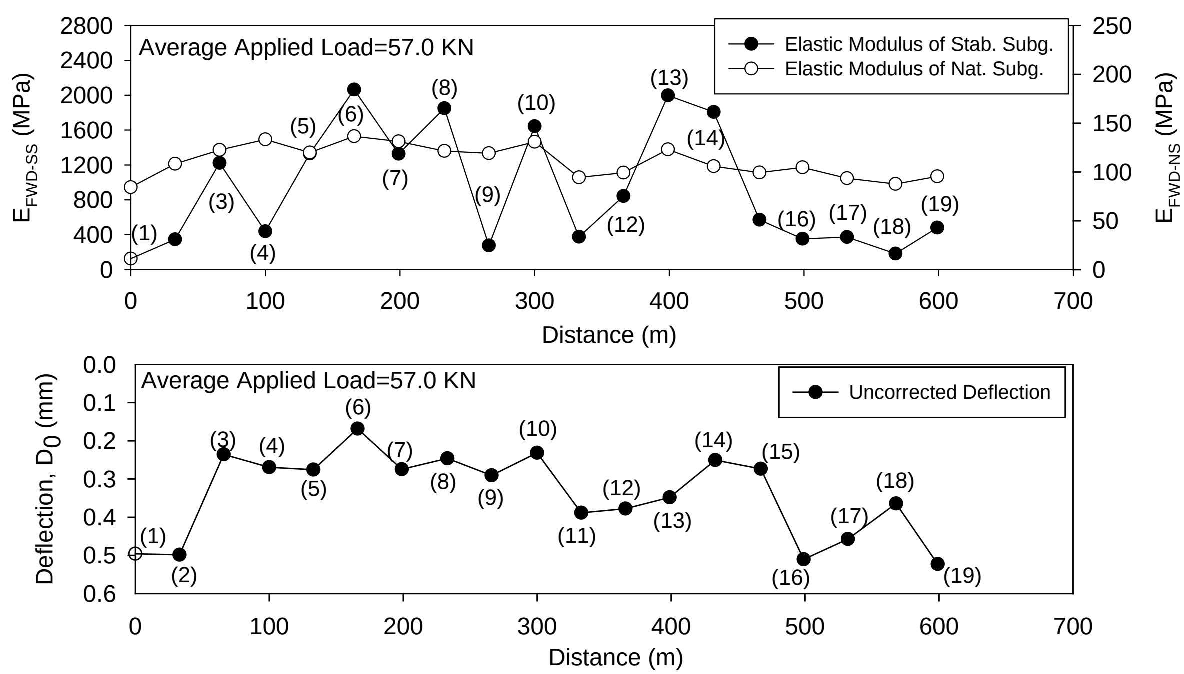


Figure 49. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

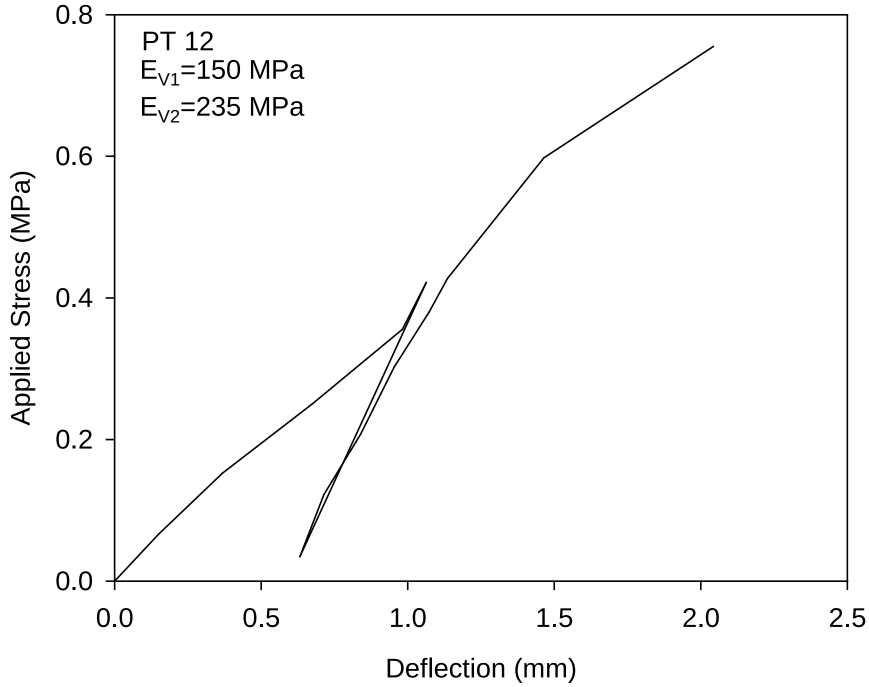


Figure 50. Corrected stress – strain curve from plate load test at point 12

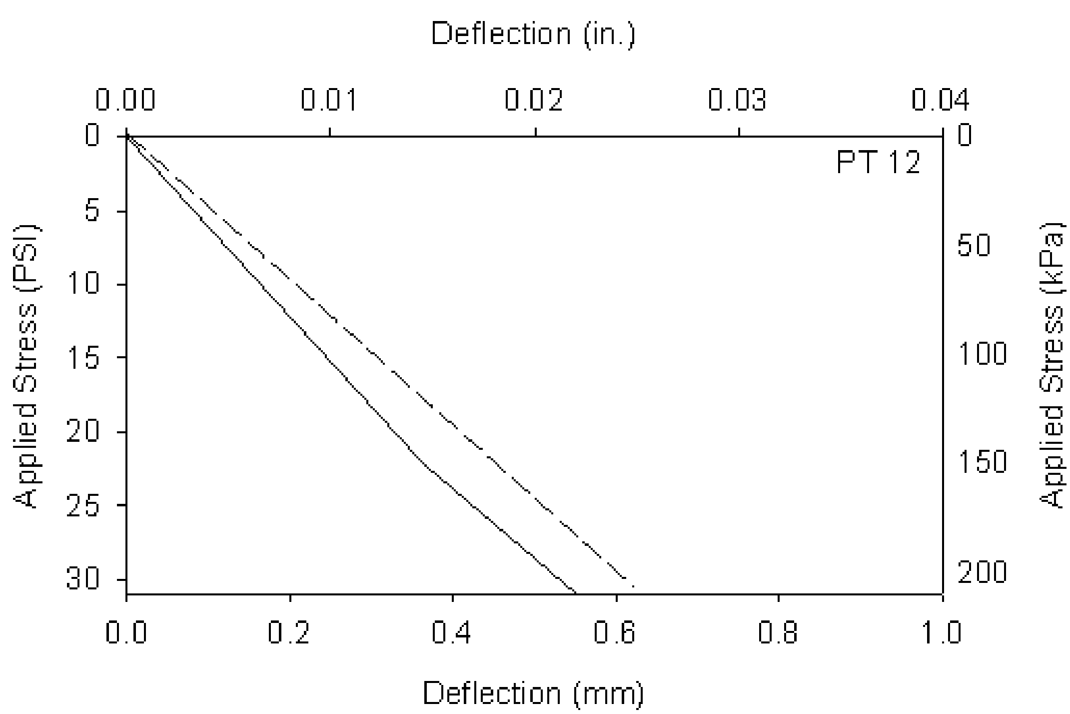


Figure 51. Stress – strain curves for obtaining K_U at point 12

Table 16. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
PT 12	Base	Top of base	102	
PT 12	Base	60 mm from top of base	112	107
PT 12	Base	95 mm from top of base	102	
PT 12	Stab. Subgrade	Top of stabilized subgrade	65	65

Table 17. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio	
CBR	E_{FWD}
7.4	8.3

Table 18. Summary statistics of test results from in-situ testing

Statistic	Base		Stabilized Subgrade							Natural Subgrade	
	CBR	E_{LWD}	CBR	E_{FWD}	k_U	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	CBR
	%	MPa	%	MPa	kPa/mm	MPa	MPa	MPa	mm	MPa	%
Number of Measurement (n)	2	1	2	19	1	1	1	1	1	19	1
Mean Value (μ)	97	107	163	926	126	65	150	235	400	111	22
Standard Deviation (σ)	52	—	18	685	—	—	—	—	—	17	—
Coefficient of Variation COV (%)	53	—	11	74	—	—	—	—	—	15	—

US 183, OK

Site Description

This project was located on the south bound driving lane of US 183 near south of Clinton, in Washita County, Oklahoma. The general location of this site is shown in Figure 52. This road is a four-lane U.S. Highway. The design life of pavement is 20 years, equivalent single axle loads (ESALS) was 10.6 million, and annual average daily traffic was 4400 in 1998 and estimated to be 6600 in 2018. The road was constructed in 1999, and a HMA overlay with a thickness of 50 mm (2 in.) was placed in 2009. The pavement originally consisted of a 254 mm (10 in.) thick asphalt concrete (AC) and 203 mm (8 in.) lime stabilized subgrade. The pavement currently consists of a 300 mm (12 in.) thick asphalt concrete (AC), and 203 mm (8 in.) lime stabilized subgrade (Figure 53). No base layer was presented in between subgrade and ACC pavement. The length of this test section is approximately 300 m (984 ft). The subgrade was stabilized with 5% lime from station 385+00 to 641+00. ISU research team conducted in-situ testing between station 407+00 to 414+00 on September 28th, 2010 with assistance and traffic control provided by Oklahoma DOT.

The plan view of in-situ test locations is shown in Figure 54. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 10 m from test points 1 to 25. DCP were conducted at test points 1, 3, 8, 9, 12, 15, 18, and 25. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 8. Bag samples were collected at test point 8 from the top to a depth of 300 mm (12 in.) of subgrade at intervals of 50 to 75 mm (2 to 3 in.). Natural subgrade samples were also collected at test points 26, 27, and 28.

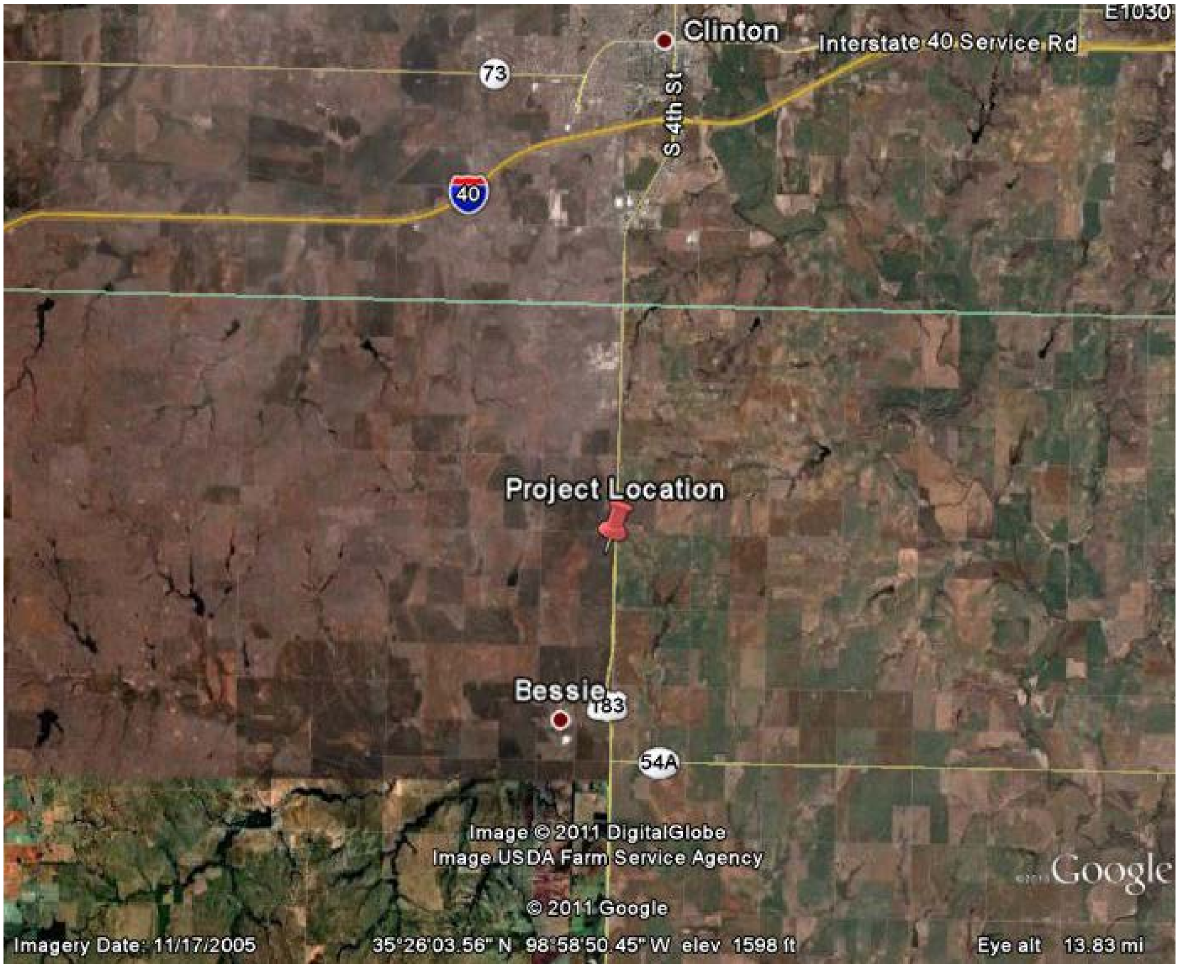


Figure 52. Project location of US 183

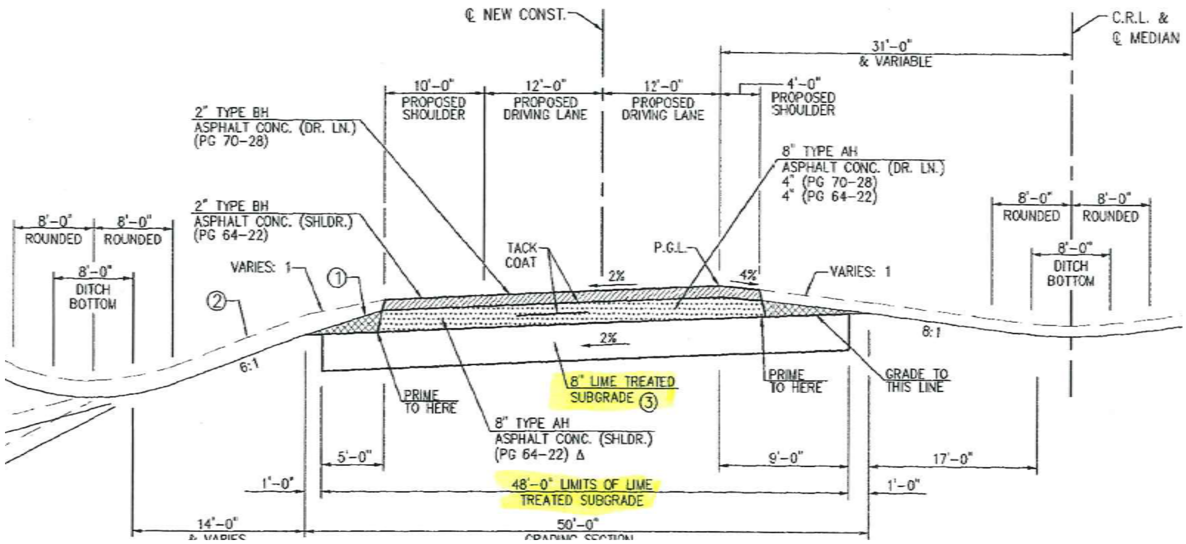


Figure 53. Typical cross section

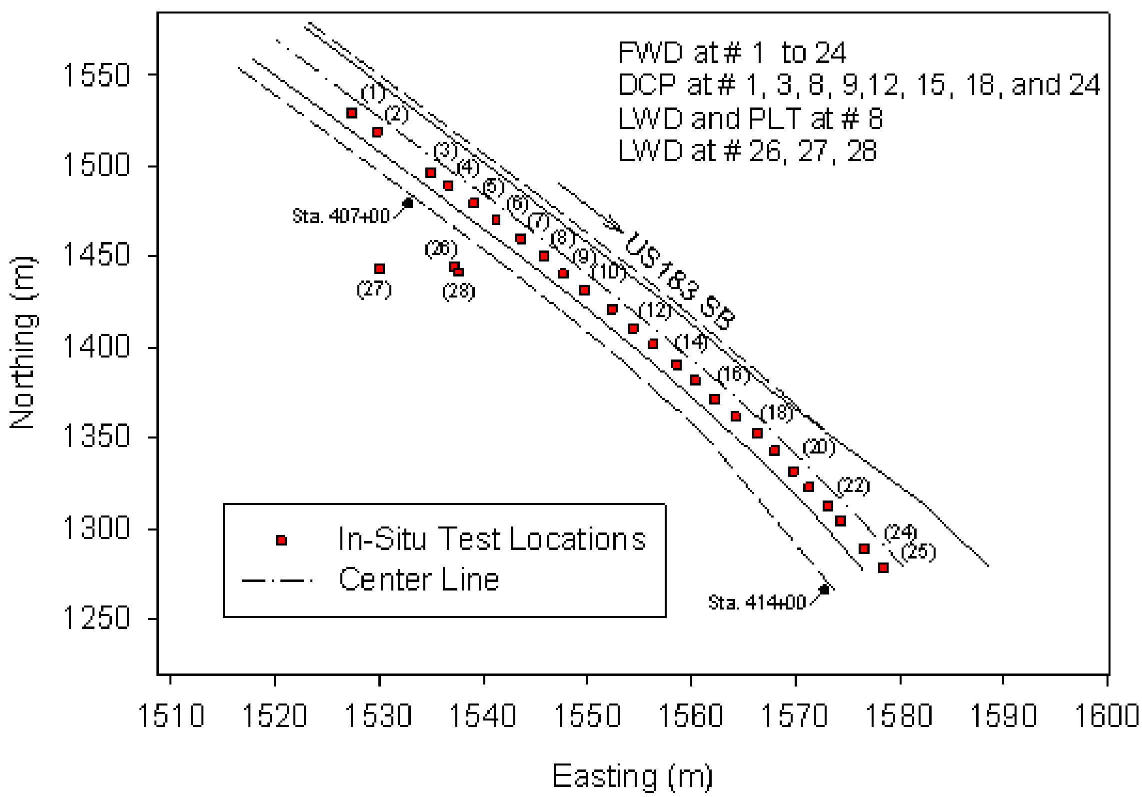


Figure 54. Test section plan layout

Figure 55. Site overview

Test Results and Analysis

Material Properties of Subgrade

The stabilized subgrade samples were taken from different depths at test point 8. The natural subgrade sample was taken at test point 26. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4, and the stabilized subgrade was classified as SM, A-4, and A-2-4. The summary of material properties of subgrade is provided in Table 19. The gravel content increased from about 1.5% to 25%, and the sand content increased from about 14.2% to 40%. The clay content decreased from about 15.9 % to 4.9 %, and the silt content decreased from about 68.4% to about 30%. LL values of stabilized and natural subgrade samples were approximately equal. PI values of stabilized subgrade samples were about 3-4 smaller than those of natural subgrade. The moisture content was around 20% for the stabilized subgrade and 10% for the natural subgrade. Figure 56 shows particle size distribution curves of different subgrade layers. Test results show the soil type of subgrade has been modified after treatment. In-situ density and moisture content of some test points were recorded during construction shown in Appendix G.

Table 19. Summary of material properties

Parameter	US 183 OK					
Material Description	Natural Sub.	Stab. Sub.	Stab. Sub.	Stab. Sub.	Stab. Sub.	Sub.
Depth mm (in.)	—	0-90 (0-3)	90-140 (3-5)	140-191 (5-7)	191-254 (7-9.5)	254-305 (9.5-11.5)
Gravel (%) (> 4.75mm)	1.5	25.1	28.8	25.9	19.4	13.9
Sand (%) (4.75mm-75μm)	14.2	39.4	42.7	39.5	39.4	31.5
Silt (%) (75μm–2μm)	68.4	30.6	24.7	30	35.2	46.2
Clay (%) (< 2μm)	15.9	4.9	3.8	4.6	6	8.4
C_u	—	286	407	321	184.5	57.9
C_c	—	0.2	0.5	0.2	0.3	0.7
Liquid Limit, LL (%)	33.9	34.7	37	34.5	35.9	30.5
Plasticity Index, PI	10.2	6.5	8.8	5.4	4.5	6.7
AASHTO	A-4	A-4	A-2-4	A-2-4	A-4	A-4
USCS	ML	SM	SM	SM	SM	ML
Water Content (%)	9.9	22.2	22.3	21.0	21.0	18.0

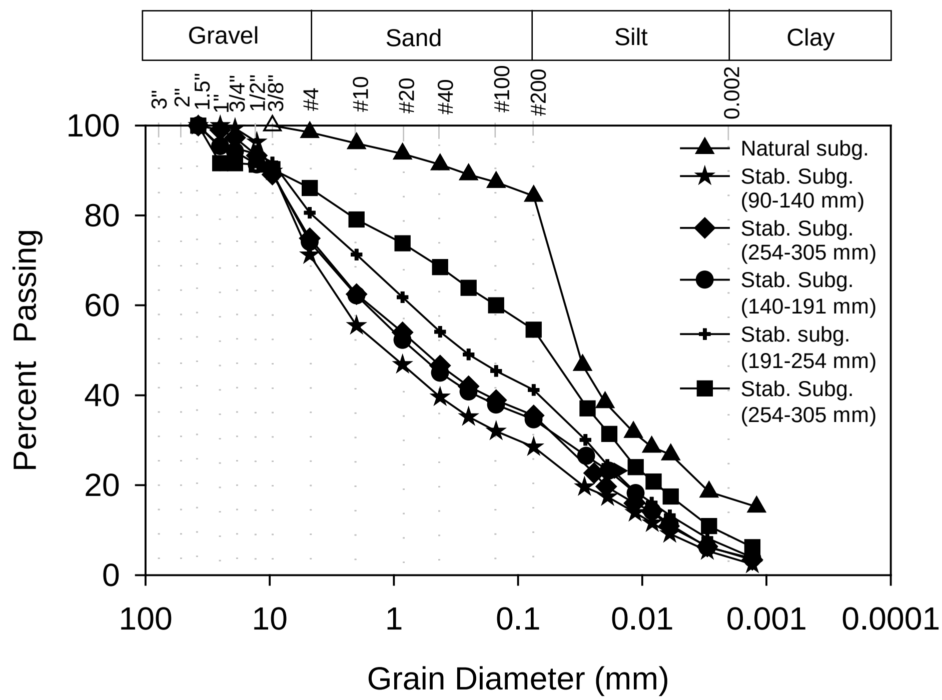


Figure 56. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Figure 57 shows the pH profile of subgrade at test point 8. The pH values of stabilized subgrade varied from 8.1 to 8.9. The pH value of natural subgrade varied from .7.9-8.3. A general trend is followed from higher to lower pH from the top stabilized to natural subgrade.

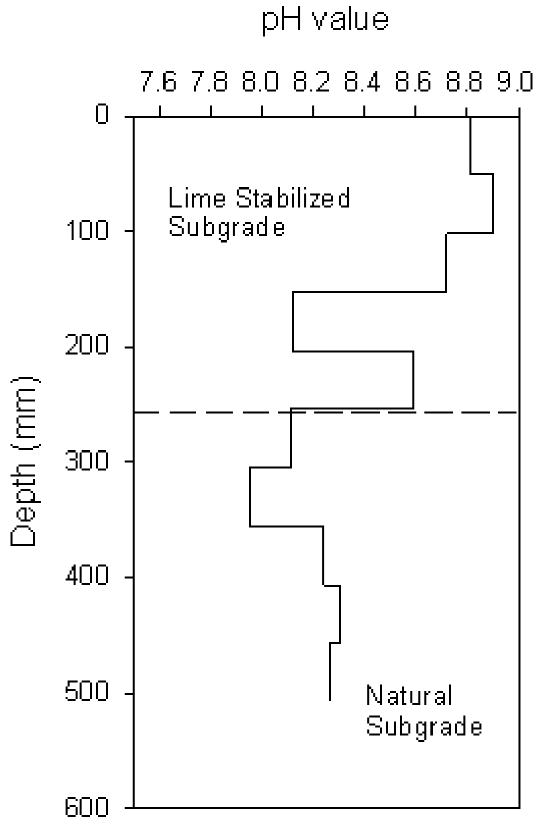


Figure 57. pH profile of subgrade

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 58. The majority elements were calcium (Ca), silica (Si), alumina (Al), and oxygen (O). These elements are commonly existed lime stabilized subgrade. Additional present elements were iron (Fe), potassium (K), and Sodium (Na).

Figure 59 compares element concentration in Al, Si, O, S, Mg, Ca, K, and C for stabilized and natural subgrade. Natural subgrade sample shows less concentration of Ca and C, and higher concentration of Si, Al, O, and Mg.

SEM images of natural and stabilized subgrade samples at 5000×maginification are shown in Figure 60 and Figure 62. SEM images of natural and stabilized subgrade samples at

15000×maginification are shown in Figure 61 and Figure 63. The natural subgrade sample shows particle with thin wave, flakes arrangement, and some pore space. The stabilized subgrade sample shows particle with blocked type particles, platy shape and some opening. Others SEM images are presented in Appendix D.

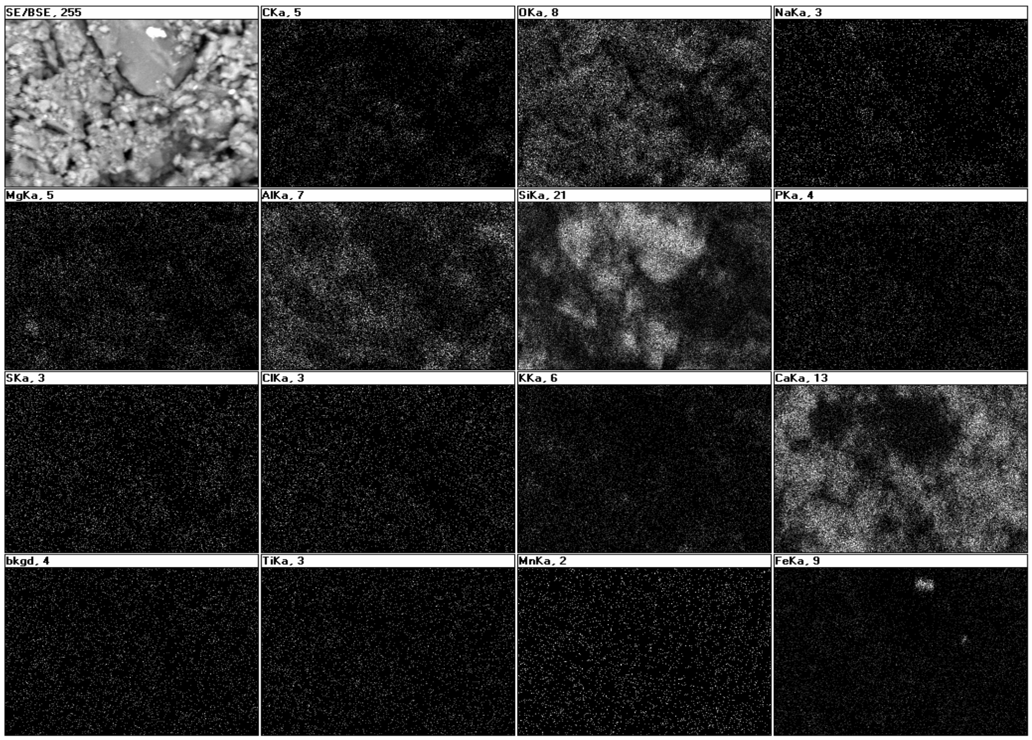


Figure 58. EDS map of stabilized subgrade sample (1500 ×)

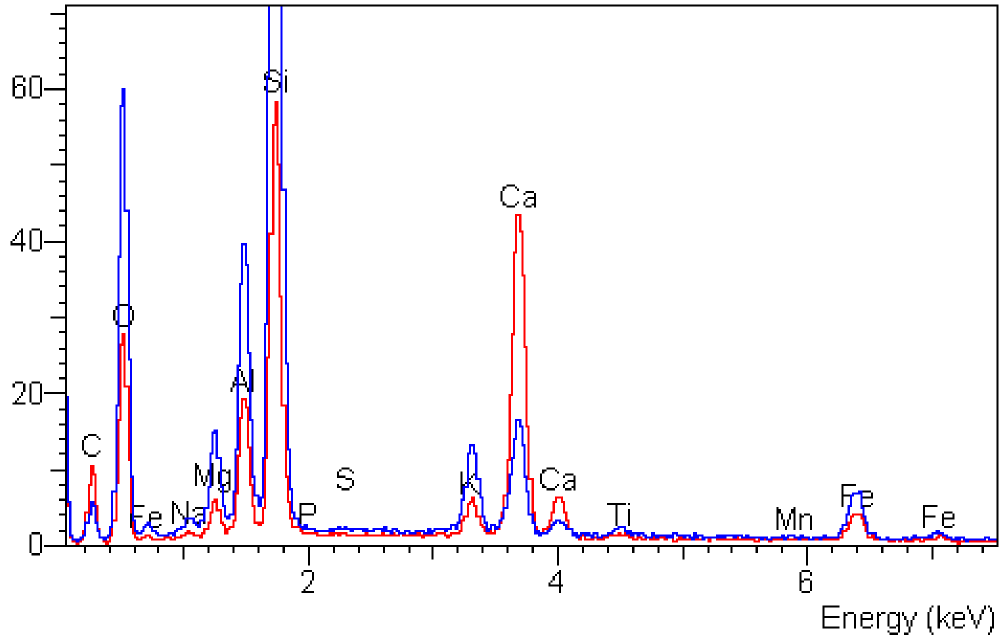


Figure 59. EDS intensity counts for stabilized subgrade sample (red line: 30×) and natural subgrade sample (blue line: 30×)

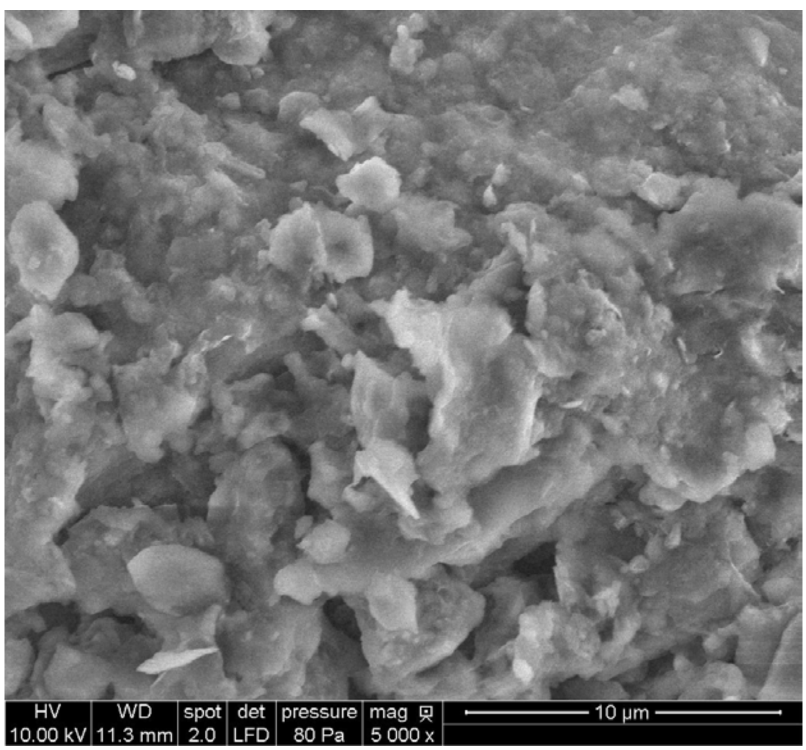


Figure 60. SEM image of natural subgrade sample (5000×)

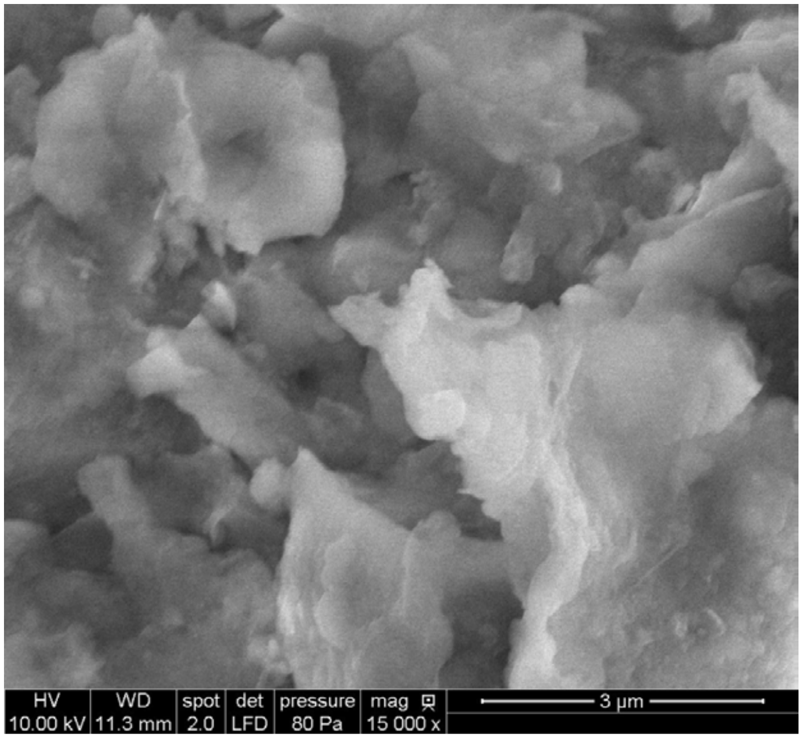


Figure 61. SEM image of natural subgrade (15000×)

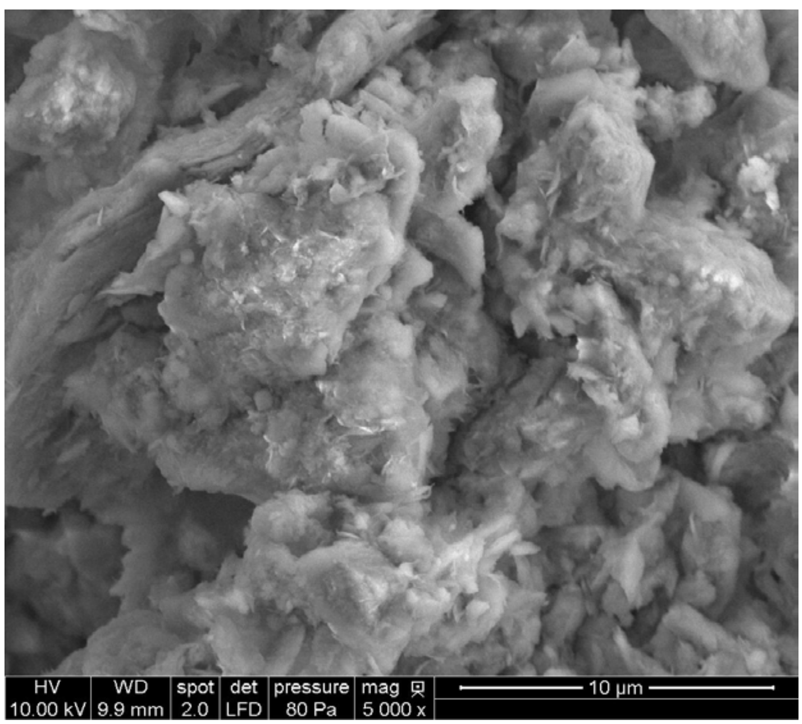


Figure 62. SEM image of stabilized subgrade sample (5000×)

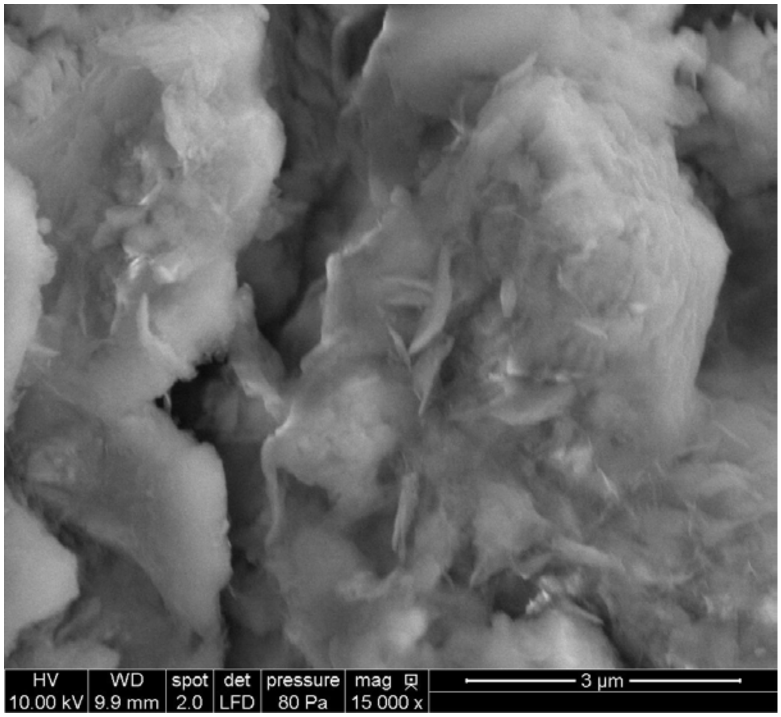


Figure 63.SEM image of stabilized sample (15000×)

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). CBR-DCP profile and cumulative drops versus CBR are shown Figure 64. Average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 65. The major observations are: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 133%, (2) the average CBR of the natural subgrade ranged from 21 to 34, (3) the CBR of the stabilized subgrade was 270-630% greater than the natural subgrade, (4) the top and bottom layer of stabilized subgrade has a lower CBR than the middle layer, and (5) the actual treatment thickness was thicker than the design value.

Backcalculated subgrade elastic moduli (E_{FWD}) and deflections were presented in Figure 66. In the backcalculation, the applied test load was 57 KN (12800 lb). The assumptions of poison’s ratio were 0.35, 0.40, and 0.40 for ACC surface layer, stabilized subgrade, and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The temperature of middle depth of ACC pavement is 24 ^{0}C (75 ^{0}F). Deflections under the loading plate (D_0) were adjusted to a standard temperature of 20 ^{0}C (68 ^{0}F) using Equation (5). The key findings are:

- The average D_0 was about 0.15 mm under average applied load of 57 KN (12814 lb). As D_0 decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 144 MPa for natural subgrade and increased to 1794 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 1200% of natural subgrade
- The values of E_{FWD} of natural and stabilized subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 67 presents the stress-strain relationship of PLT at test point 8. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 68. The correction of k′u was made using the curve in Figure 8.

Table 20 provides all LWD elastic modulus (E_{LWD}) at four test points. The average E_{LWD} was increased 863% from 19 MPa for natural subgrade to164 MPa for stabilized subgrade. E_{LWD} of stabilized subgrade was equal to 0.5 E_{V1} and 0.3 E_{V2}. Table 21 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 22. All in-situ test results are presented in Appendix F.

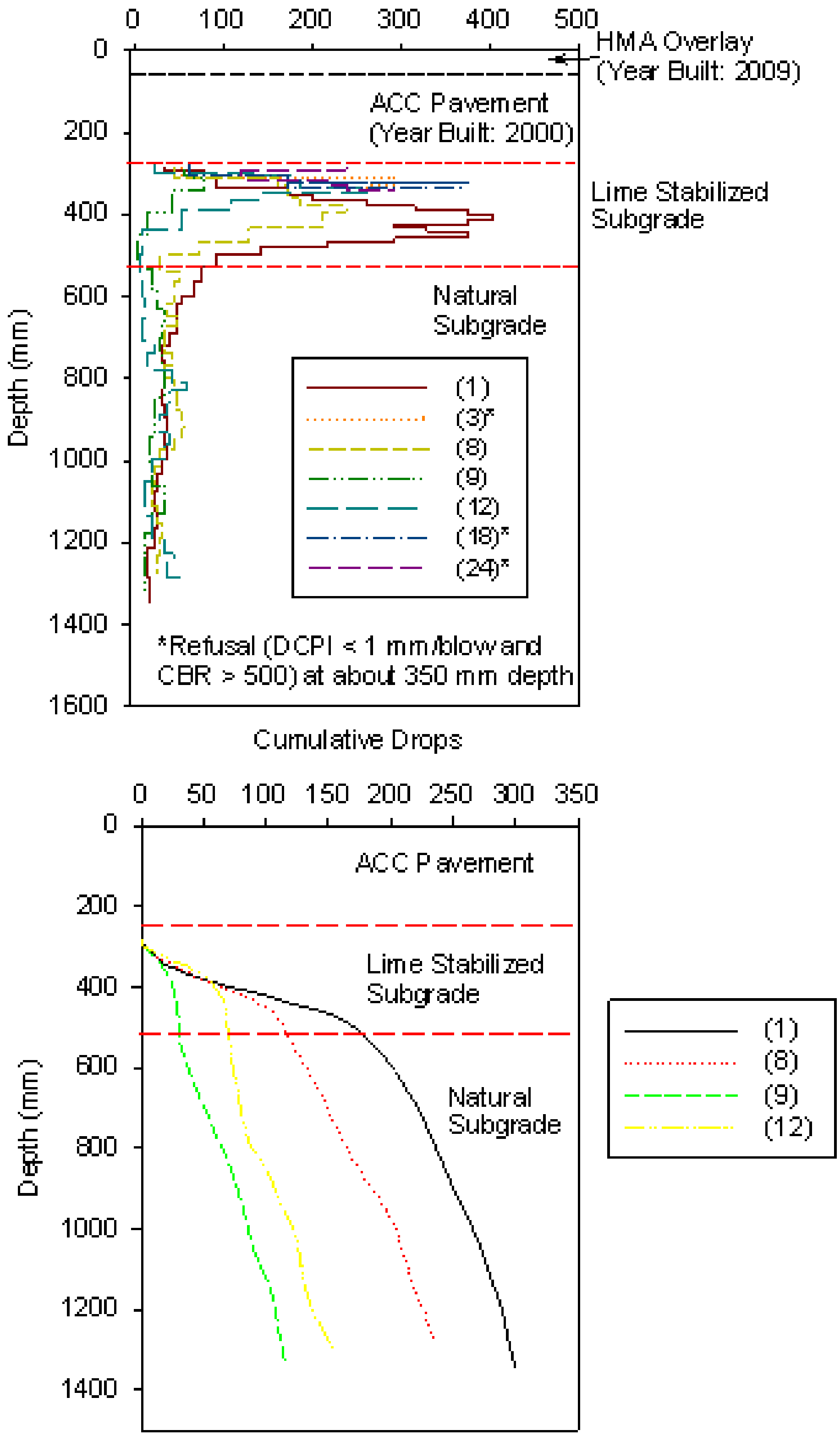


Figure 64. CBR – DCP profile and cumulative drops versus CBR of test points

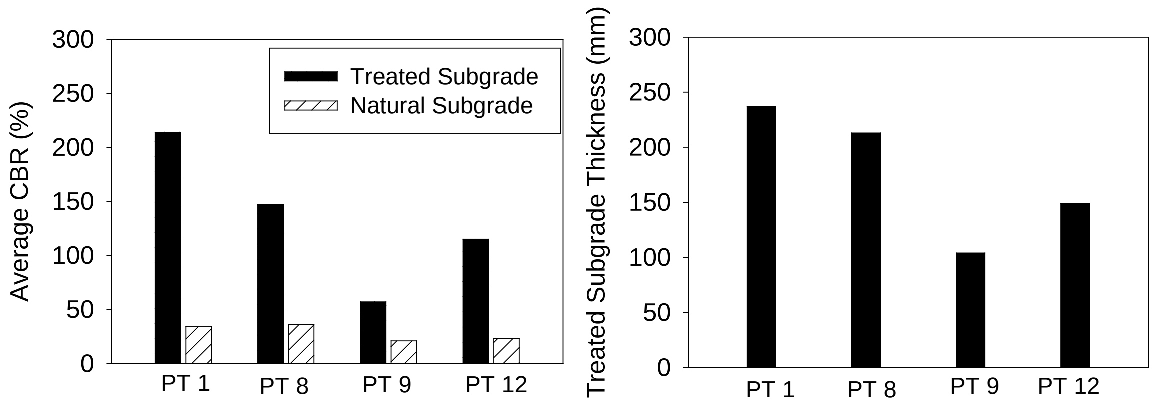


Figure 65. CBR and stabilized subgrade thickness from DCP profile

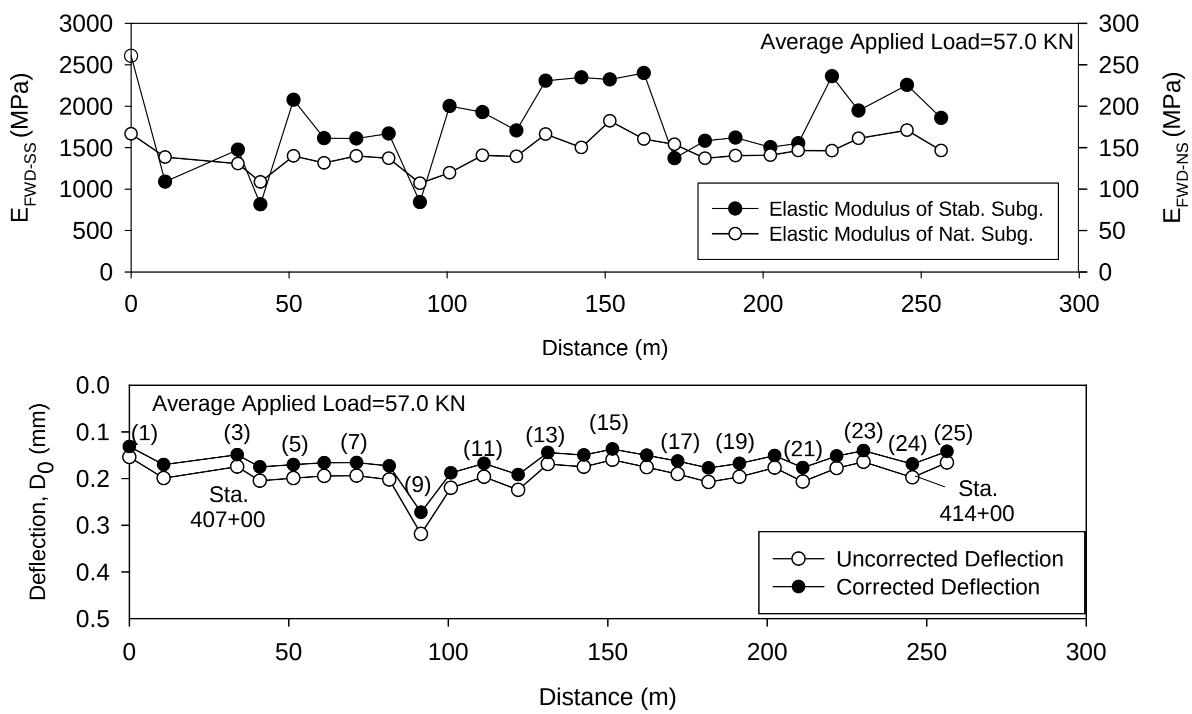


Figure 66. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

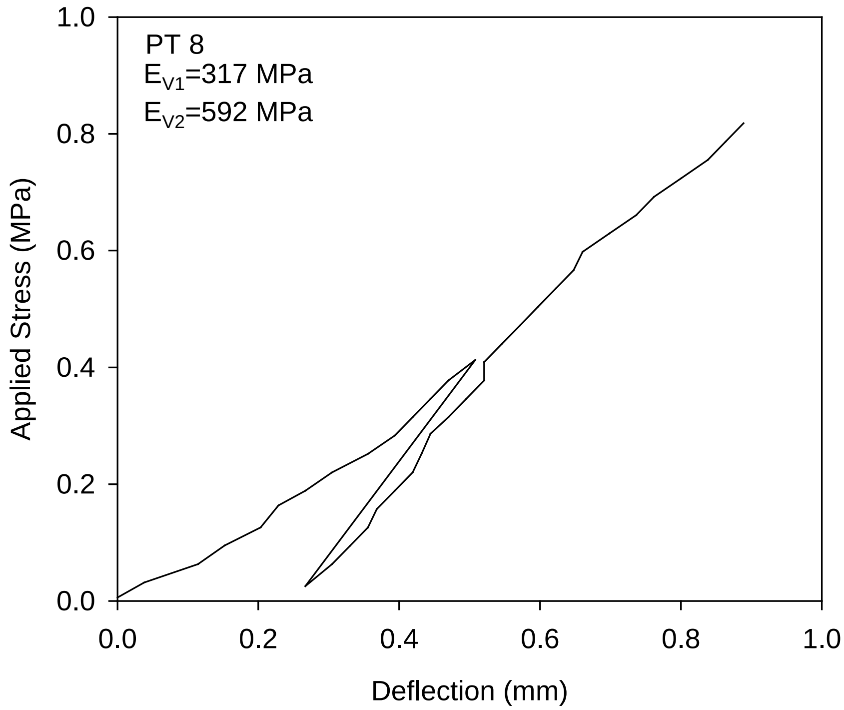


Figure 67. Stress – strain curves from plate load test at point 8

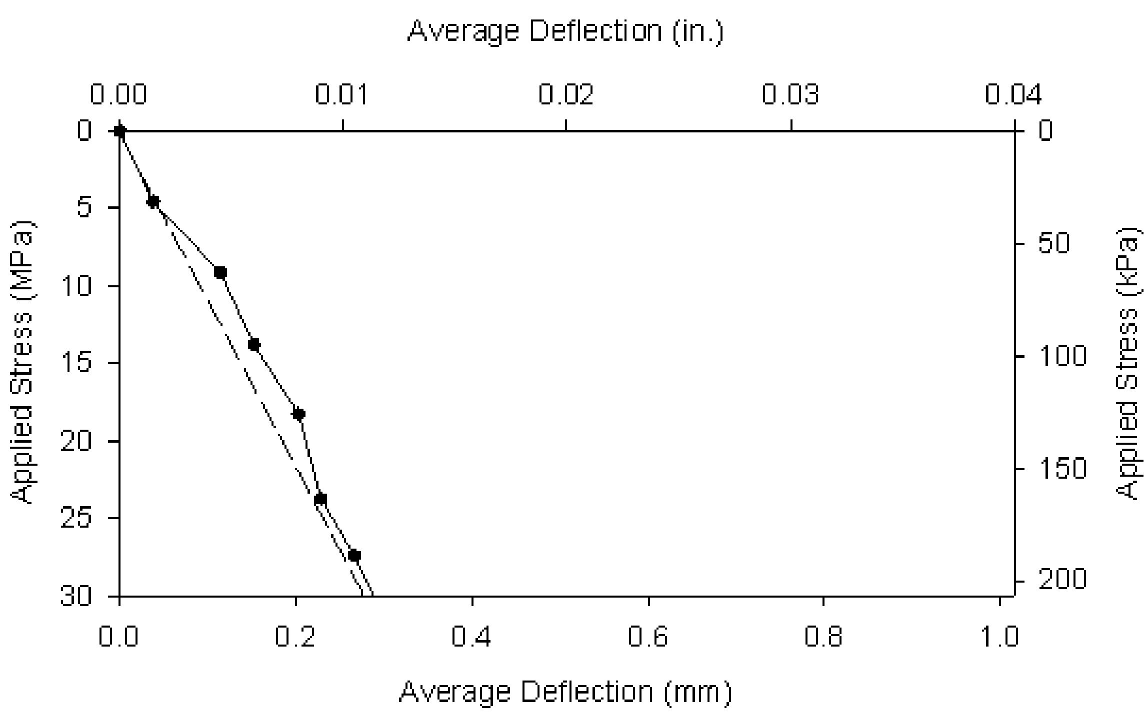


Figure 68. Stress – strain curves for obtaining K_U at point 8

Table 20. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
8	Stabilized Subgrade	Top of stabilized subgrade	164	164
26	Natural Subgrade	Top of natural subgrade	20	15
27	Natural Subgrade	Top of natural subgrade	13	
28	Natural Subgrade	Top of natural subgrade	13	

Table 21. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio		
CBR	E_{FWD}	E_{LWD}
4.5	12.3	8.5

Table 22. Summary statistics of test results from in-situ testing

Statistic	Stabilized Subgrade							Natural Subgrade			FWD Def
Measurement	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	Thi.	CBR	E_{FWD}	E_{LWD}	$D_{0\text{-}Cor.}$
	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	MPa	mm
Number of Measurement (n)	4	25	1	1	1	1	4	4	25	3	25
Mean Value (μ)	133	1794	164	317	592	202	176	29	144	19	0.17
Standard Deviation (σ)	65	480	—	—	—	—	61	8	18	5	0.03
Coefficient of Variation COV (%)	49	27	—	—	—	—	34	27	12	25	17

SH 99, OK

Site Description

This project was located on the north bound driving lane of SH 99 near north of Seminole in Seminole County, Oklahoma. The general location of this site is shown in Figure 69. This road is a four-lane State Highway. The design life of pavement is 20 years, and annual average daily traffic was 6800 in 1991 and estimated to be 12000 in 2011. The road was constructed in 1999. The length of this test section is approximately 500 m (1640 ft). The pavement consisted of a 254 mm (10 in.) thick asphalt concrete (AC), and 152 mm (6 in.) aggregate base, and 203 mm (8 in.) subgrade stabilized with fly ash (Figure 70). ISU research team conducted in-situ testing between station 5110+00 to 5126+00 on September 29th, 2010 with assistance and traffic control provided by Oklahoma DOT.

The plan view of in-situ test locations is shown in Figure 71. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 11 m from test points 1 to 45. DCP were conducted at test points 1, 43, 44, and 45. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 45. LWD and DCP were also performed at control test point 46. Bag samples were collected at test point 45 from the top to a depth of 75 mm (3 in.) of subgrade, and natural subgrade samples were collected at control test point 46.

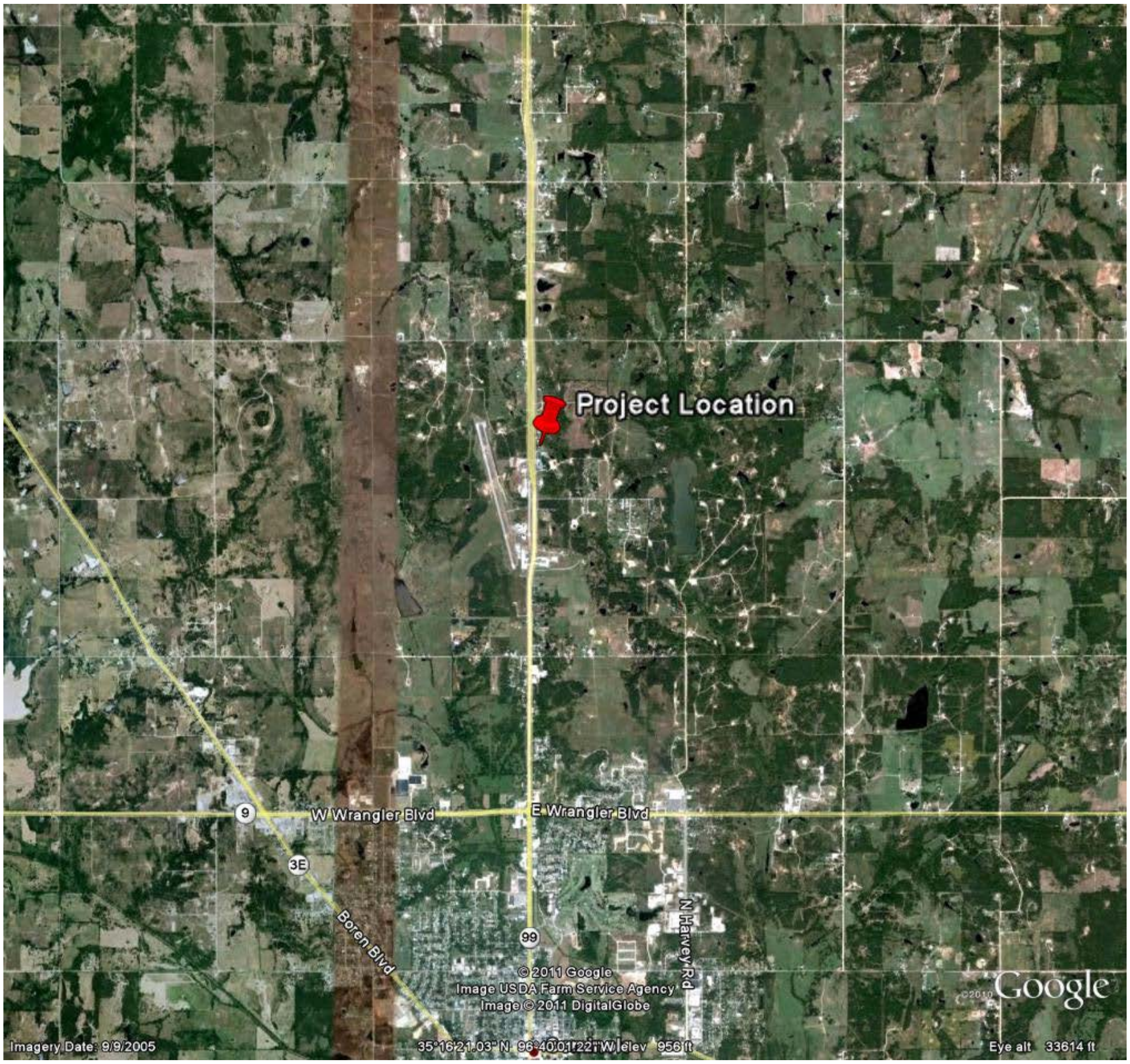


Figure 69. Project location of SH 99

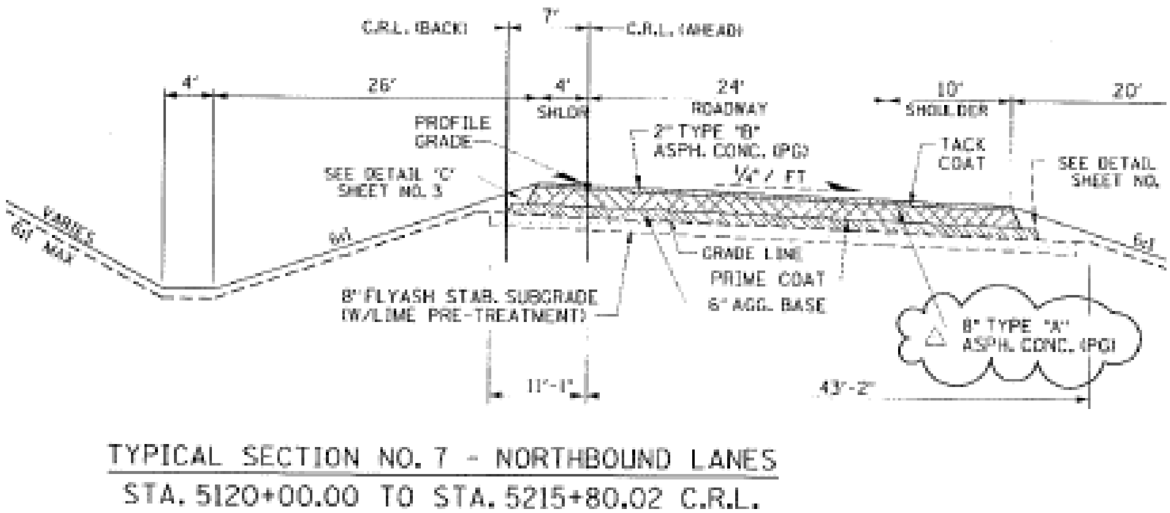


Figure 70. Typical cross section

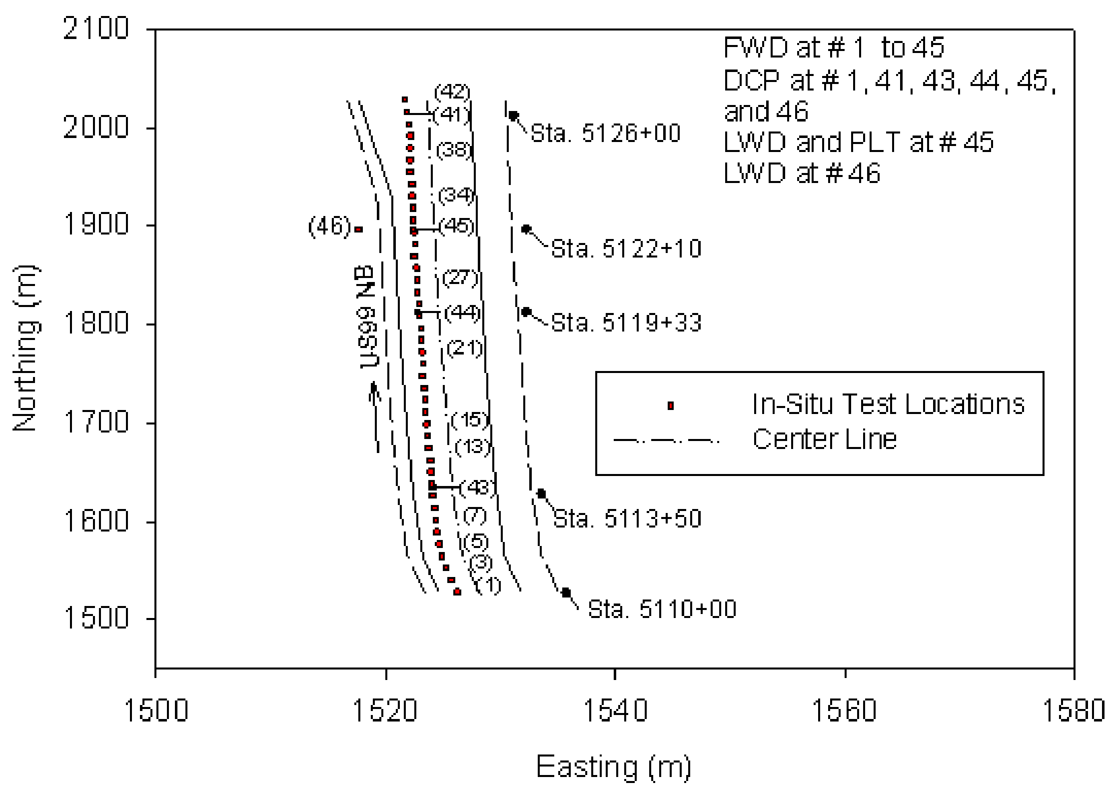


Figure 71. Test section plan layout

Figure 72. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The base and stabilized subgrade samples were taken at test point 45. The natural subgrade sample was taken at test point 46. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4-0, and the stabilized subgrade was classified as SM and A-4-0. Table 23 provides material properties of subgrade. The gravel content increased from about 3.9% to 6.7%, and the sand content increased from about 48.6% to 58.4%. Stabilized subgrade was a non-plastic soil. The moisture content was around 21% for the stabilized subgrade and 12% for the natural subgrade. Figure 73 shows particle size distribution curves of different subgrade layers. In-situ density and moisture content of some test points were recorded during construction shown in Appendix G.

Table 23. Summary of material properties

Parameter	**SH 99 OK**		
Material Description	Base	Stabilized Subgrade	Natural Subgrade
Depth mm (in.)	0-150 (0-6)	0-200 (0-8)	—
Gravel Content (%) (> 4.75mm)	64.7	6.7	3.9
Sand Content (%) (4.75mm – 75µm)	29.0	48.6	58.4
Silt Content (%) (75µm – 2µm)	5.1	35.4	27.2
Clay Content (%) (< 2µm)	1.2	9.3	10.5
Coefficient of Uniformity (Cu)	37.9	68.8	84.7
Coefficient of Curvature (Cc)	2.6	2.0	2.0
Liquid Limit, LL (%)	16.1	—	22.3
Plasticity Index, PI	4.5	N.P.	4.9
AASHTO	A-1-a	A-4-0	A-4-0
USCS	GW-GM	SM	SM
Water Content (%)	3.4	20.6	11.7

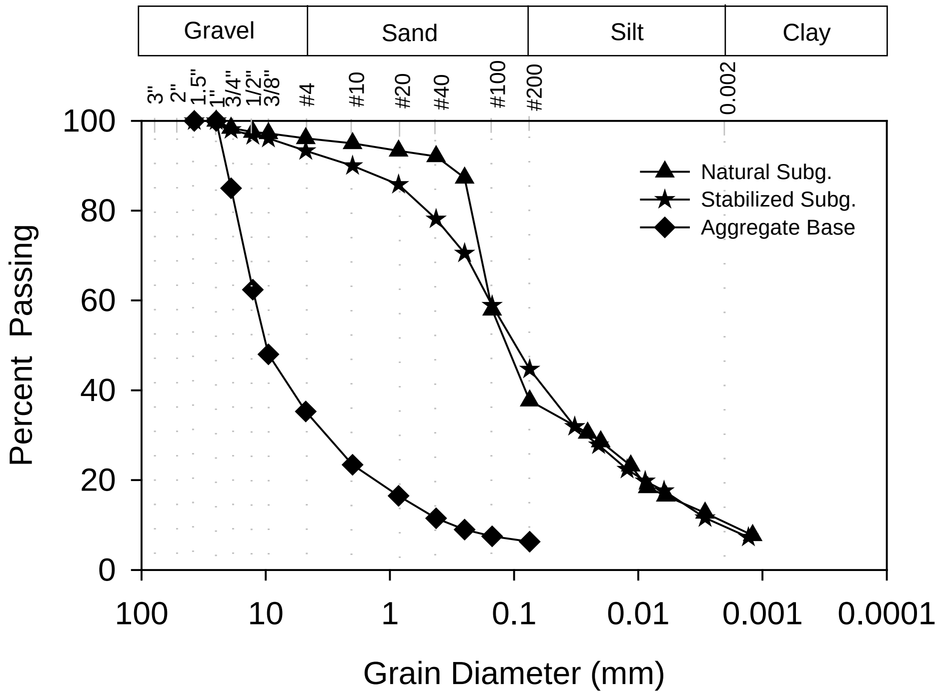


Figure 73. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Table 24 shows pH values of natural and stabilized subgrade. The natural subgrade has a high pH value of 8.2. The pH value of stabilized subgrade sample is 9.2

Table 24. Summary of pH value of subgrade

Depth	**pH value**
Natural subgrade	8.2
Stabilized subgrade	9.2

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 74. The majority elements were calcium (Ca), silica (Si), alumina (Al), and oxygen (O). Additional present elements were iron (Fe), potassium (K) and Sodium (Na).

Figure 75 compares element concentration in Al, Si, O, S, Mg, Ca, K, and C for natural subgrade. The sample shows high concentration in Si, O, and Al. Figure 76 compares element concentration for stabilized subgrade. The stabilized subgrade sample shows higher concentration of O, Ca, and Al than the natural subgrade sample. All SEM images are presented in Figure 77, Figure 78, and Appendix D.

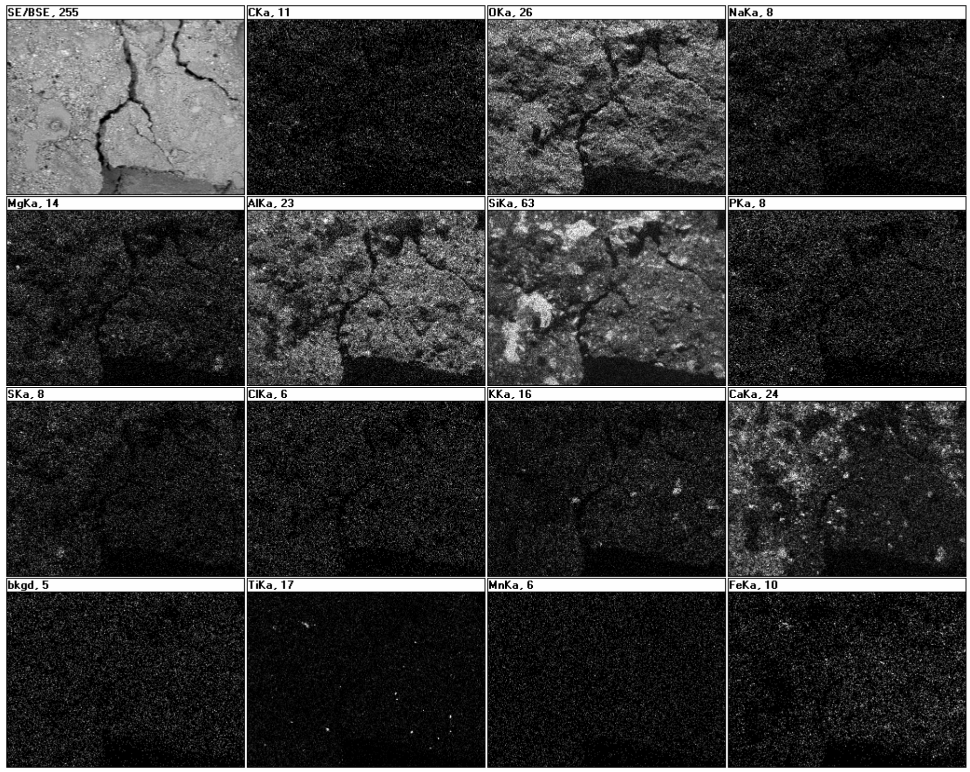


Figure 74. EDS map of stabilized subgrade sample (150 ×)

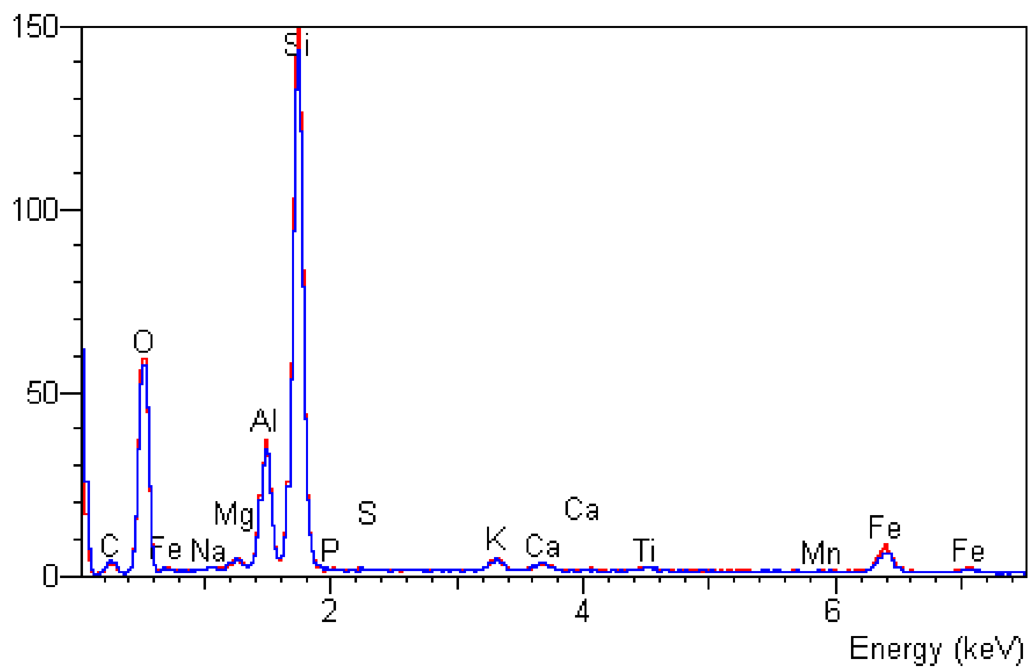


Figure 75. EDS intensity counts for natural subgrade sample (red line: 500×; blue line: 30×)

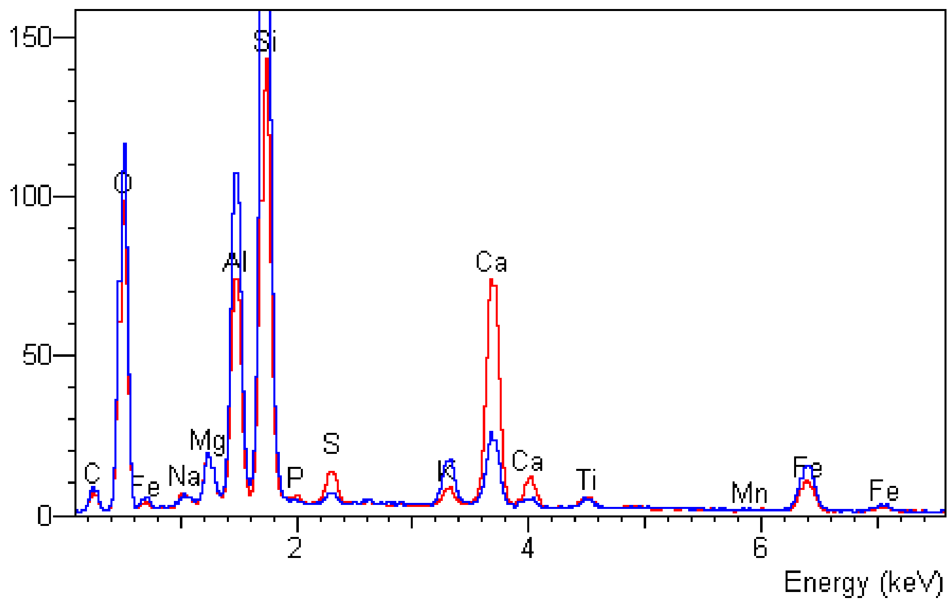


Figure 76. EDS intensity counts for stabilized subgrade sample in area a (blue line: 500×) and stabilized subgrade sample in area b (red line: 500×)

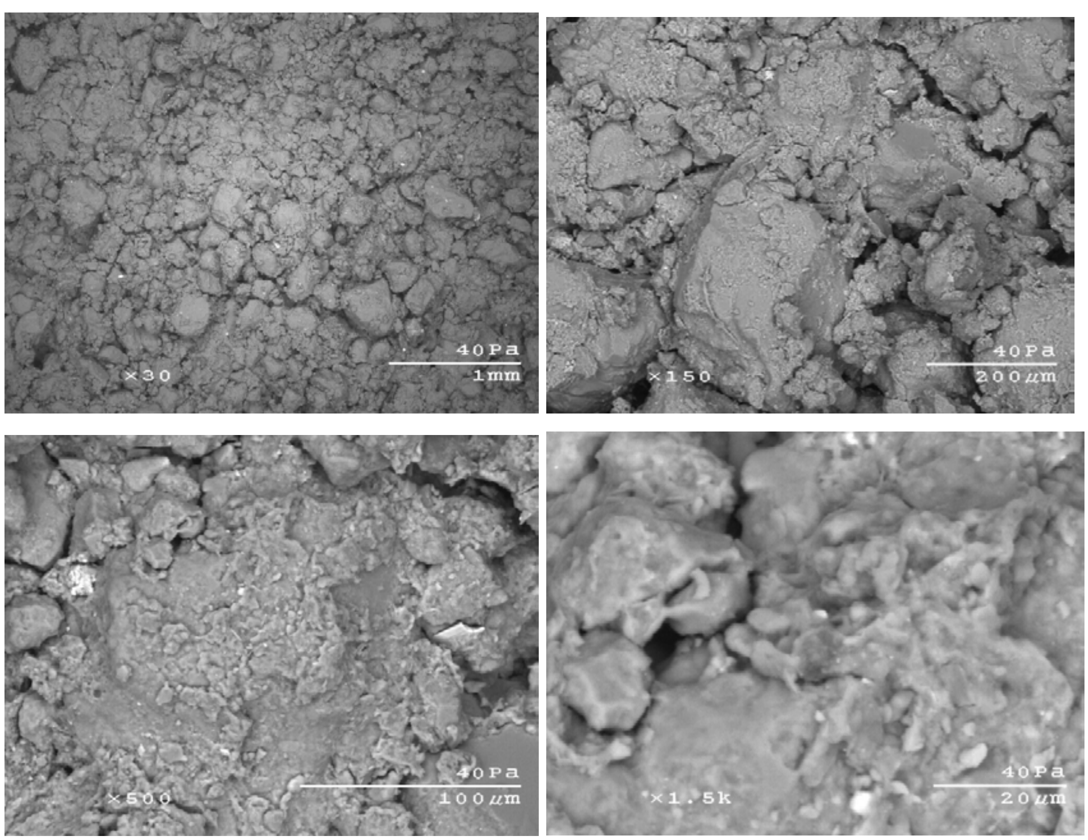


Figure 77. SEM images of natural subgrade

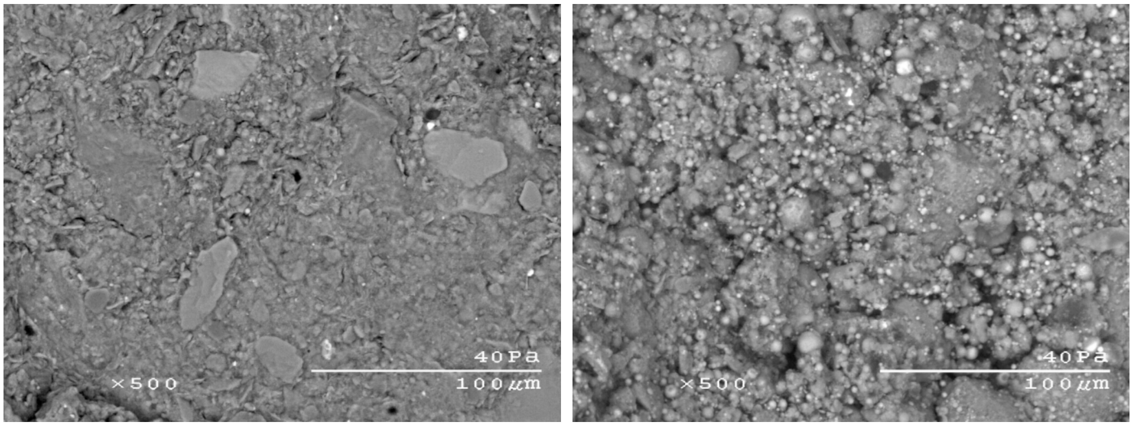


Figure 78. SEM images of stabilized subgrade in area a and b

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). CBR-DCP profile and cumulative drops versus CBR are shown in Figure 79. Average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 80. The major observations: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 103%, (2) the average CBR of the natural subgrade was 27%, (3) The average CBR of the stabilized subgrade was 380% of the natural subgrade, (4) the bottom layer of stabilized subgrade has a lower CBR than the top layer, and (5) the actual average treatment thickness was about 220 mm (8.8 in.), which was thicker the design value.

Backcalculated subgrade elastic moduli (E_{FWD}), uncorrected deflections, and corrected deflections were presented in Figure 81. In the backcalculation, the average applied test load was 57 KN (12876 lb). The assumptions of poison's ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, aggregate stabilized subgrade, and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The temperature at the middle depth of ACC pavement was 11 ^{0}C (52 ^{0}F). Deflections under the loading plate (D_0) were adjusted to a standard temperature of 20 ^{0}C (68 ^{0}F) using Equation (5). The key findings are:

- The average corrected D_0 was about 0.21 mm under average applied load. As corrected D_0 decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 238 MPa for natural subgrade and increased to 369 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 160% of natural subgrade
- The values of E_{FWD} of natural and stabilized subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 82 presents the stress-strain relationship at point 45. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 83. The correction of k′u was made using the curve in Figure 8.The average LWD elastic modulus (E_{LWD}) was 410% greater than natural subgrade. The E_{LWD} of stabilized subgrade was equal to 1.7 E_{V1} and 0.7 E_{V2}. The E_{LWD} of stabilized subgrade was 0.3 $E_{FWD.}$

Table 25 lists all LWD test results at points 45 and 46. Table 26 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 27. All in-situ test results are presented in Appendix F.

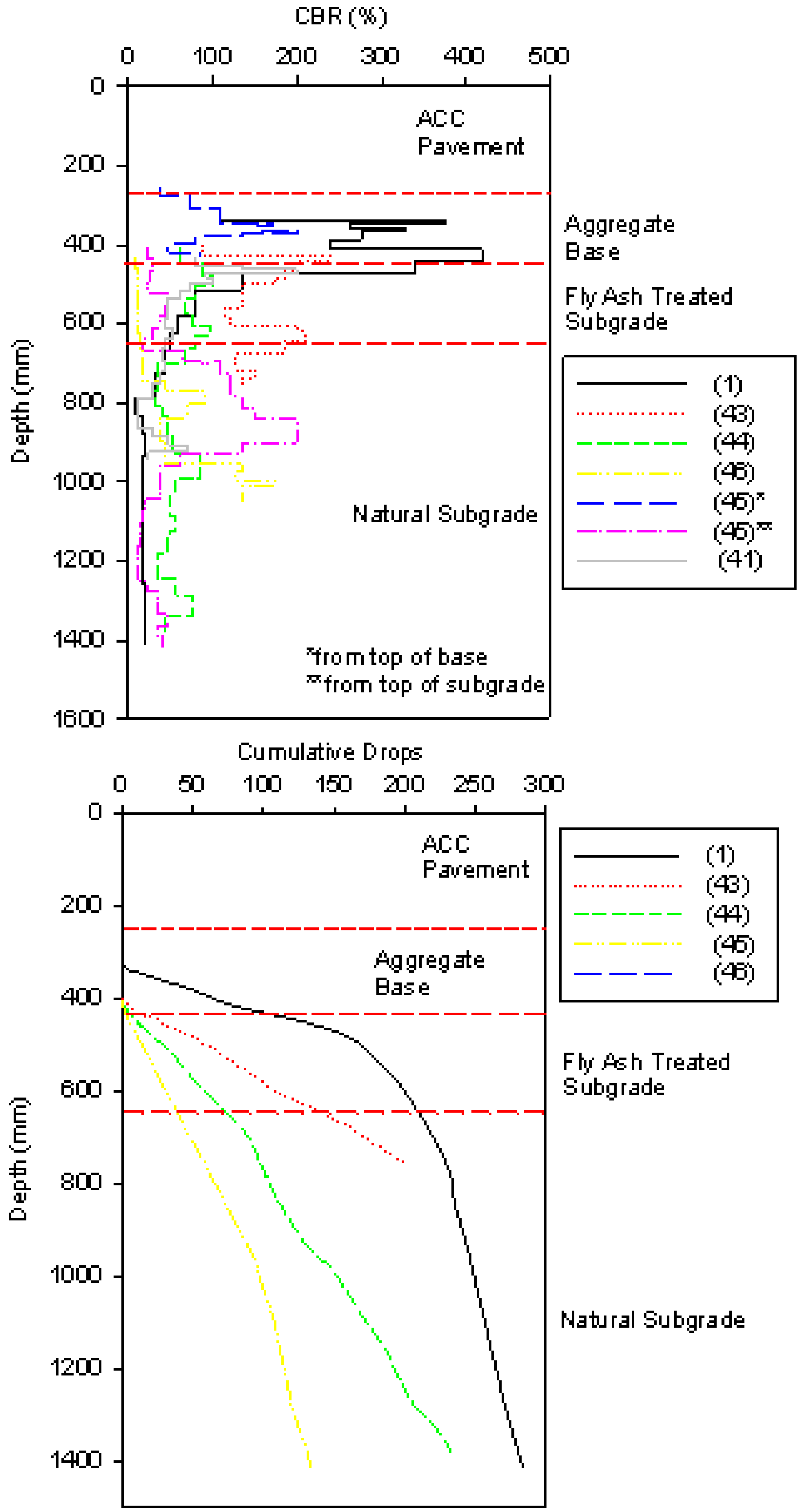


Figure 79. CBR – DCP profile of test points

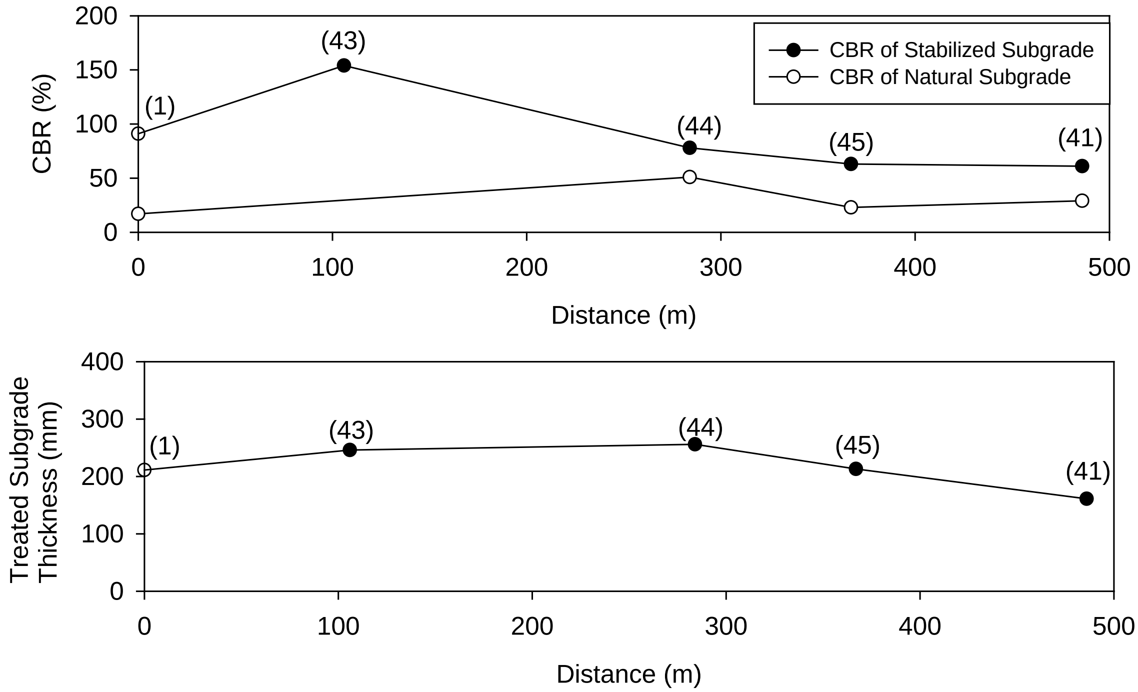


Figure 80. CBR and stabilized subgrade thickness from DCP profile

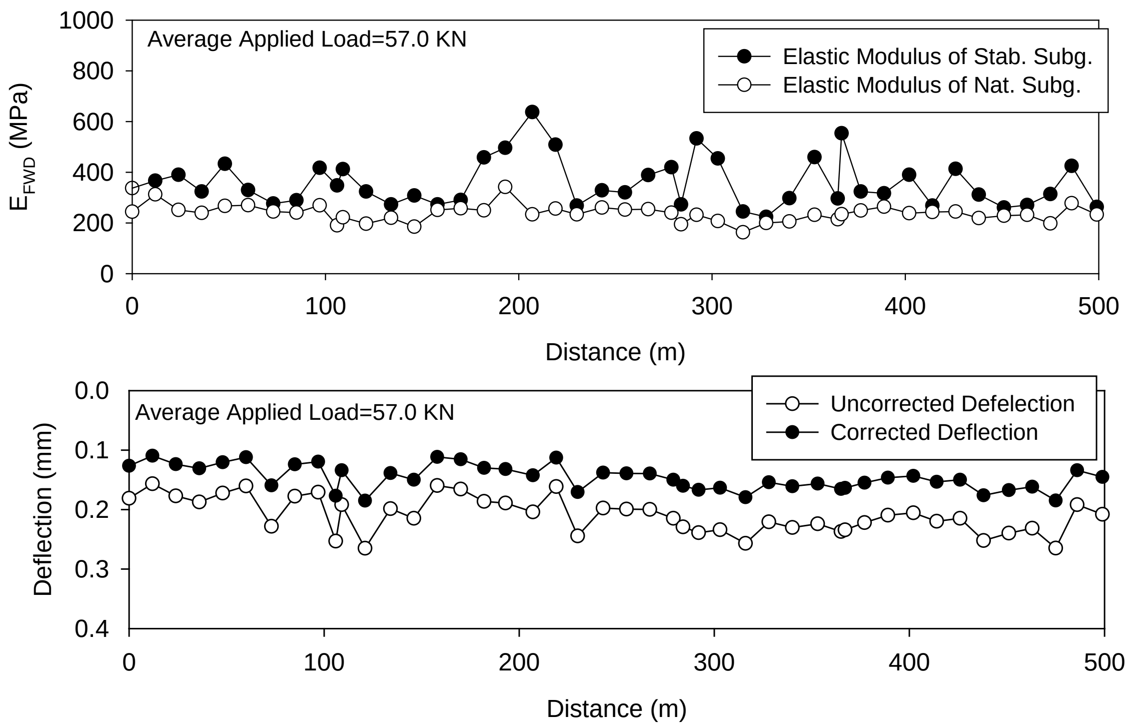


Figure 81. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

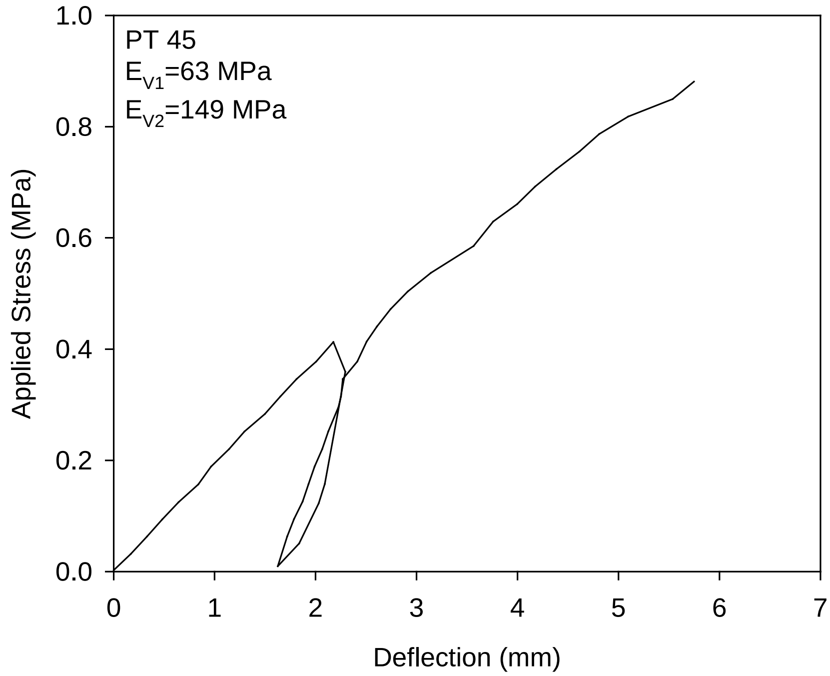


Figure 82. Stress – strain curves from plate load test at point 45

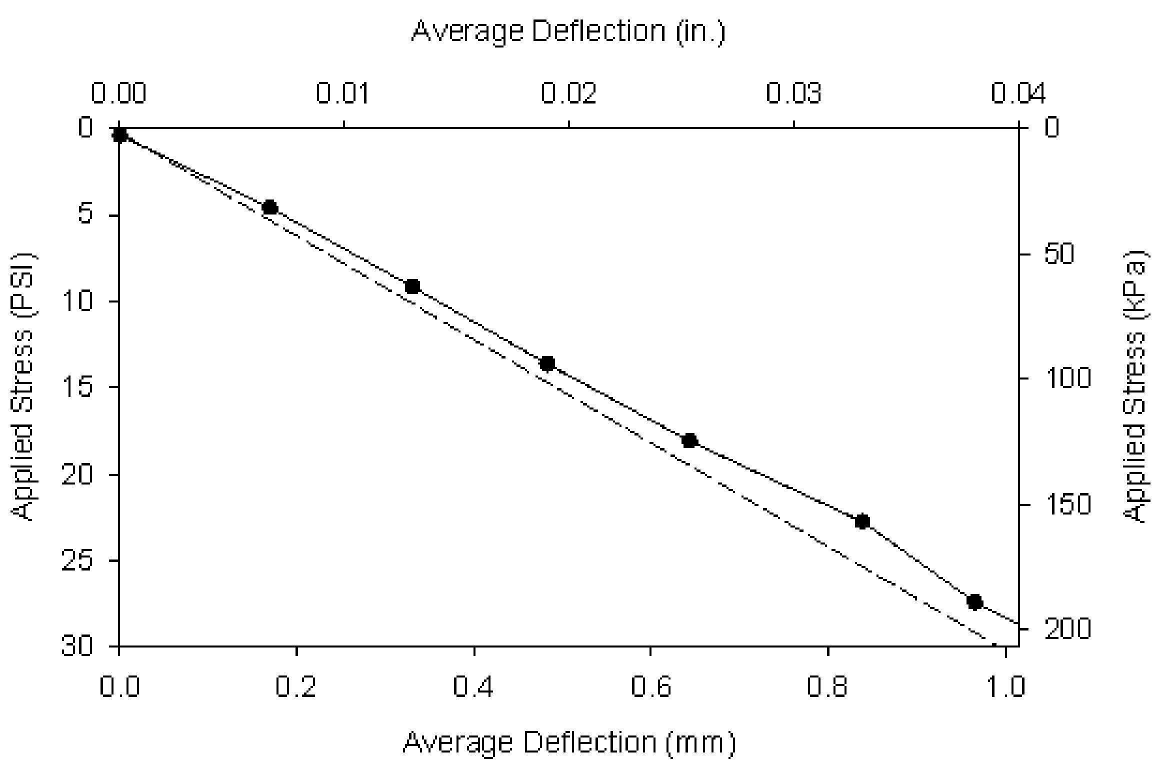


Figure 83. Stress – strain curves for obtaining K_U at point 45

Table 25. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
45	Stabilized subgrade	Top of Stabilized Subgrade	80	65
45	Stabilized subgrade	63 mm from top of stabilized subgrade	50	
46	Natural Subgrade	Top of natural subgrade	16	16

Table 26. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio		
CBR	E_{FWD}	E_{LWD}
3.8	1.6	4.1

Table 27. Summary statistics of test results from in-situ testing

Statistic	Stabilized Subgrade							Natural Subgrade		
Measurement	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	Thi.	CBR	E_{FWD}	E_{LWD}
	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	MPa
Number of Measurement (n)	5	45	2	1	1	1	5	5	45	1
Mean Value (μ)	103	369	65	63	149	78	220	27	238	16
Standard Deviation (σ)	60	132	21	—	—	—	37	17	32	—
Coefficient of Variation COV (%)	58	36	32	—	—	—	17	63	14	—

US 59, OK

Site Description

This project was located on the south bound passing lane of US 59 near north of Panama, in Le Flore County, Oklahoma. The general location of this site is shown in Figure 84. This road is a four-lane U.S. Highway. The design life of pavement is 20 years, equivalent single axle loads (ESALS) was 12.26 million, the design speed was 55 mph, and annual average daily traffic was 7500 in 1996 and estimated to be 13250 in 2016. The road was constructed in 2000. The length of this test section is approximately 500 m (1640 ft) from station 588+40 to 601+50. The pavement consisted of a 254 mm (10 in.) thick asphalt concrete (AC), and 254 mm (10 in.) aggregate base, and 203 mm (8 in.) subgrade stabilized with fly ash (Figure 85). ISU research team conducted in-situ testing on September 30th, 2010 with assistance and traffic control provided by Oklahoma DOT.

The plan view of in-situ test locations is shown in Figure 86. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 15 m from test points 1 to 31. Five DCP tests were conducted at test points 4 (Sta.600+00), 12 (Sta. 596+00), 16 (Sta. 594+00), 20 (Sta. 592+00), 24 (Sta. 590+00), and 28 (Sta. 588+40). The control points 32, 33, and 34 were selected adjacent to test point 24. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 24. LWD and DCP were also performed on control points. Bag samples were collected at test point 24 from the top to a depth of 100 mm (4 in.) of subgrade. Natural subgrade samples were also collected at test points 31, 32, and 33.

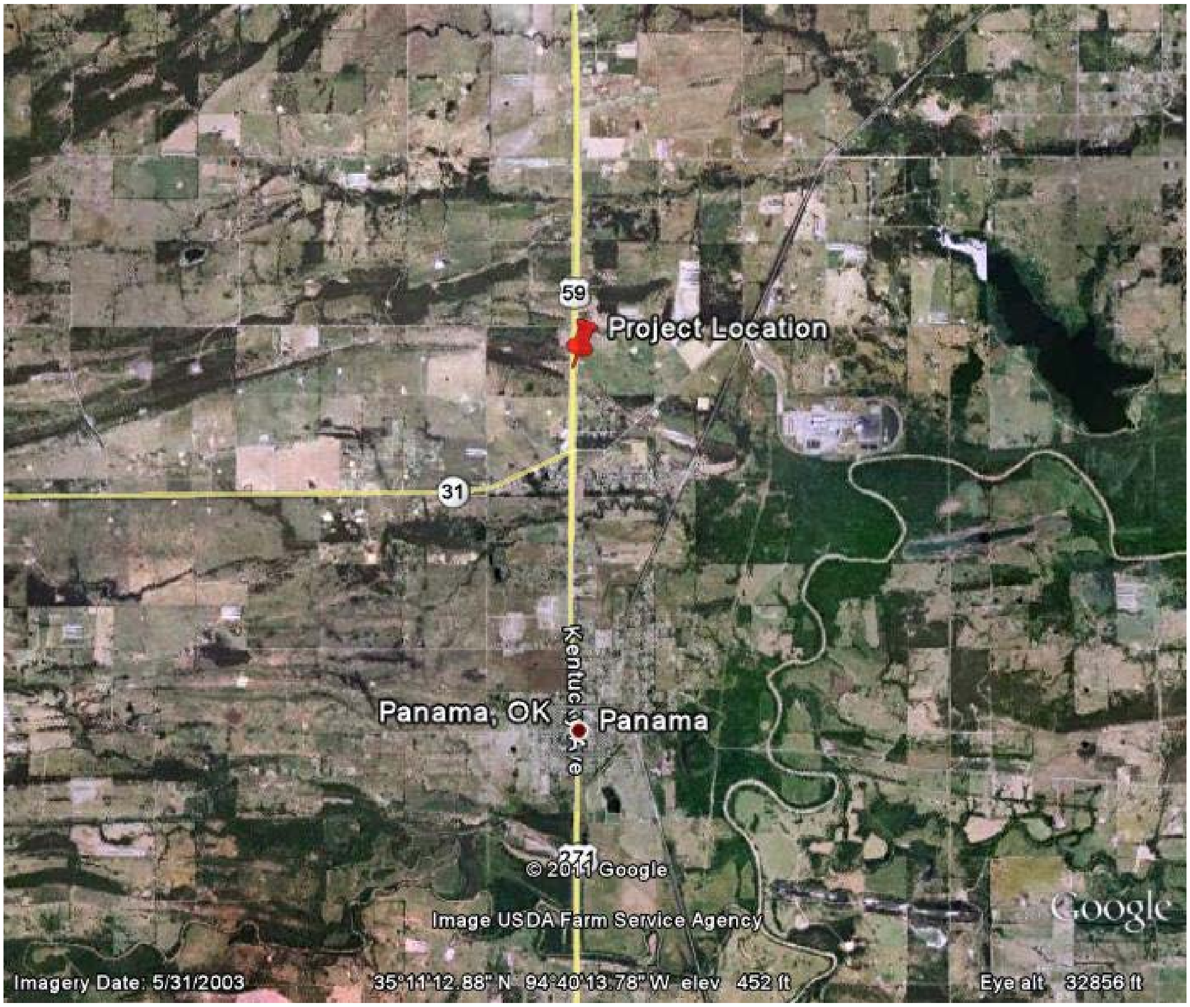


Figure 84. Project location of US 59

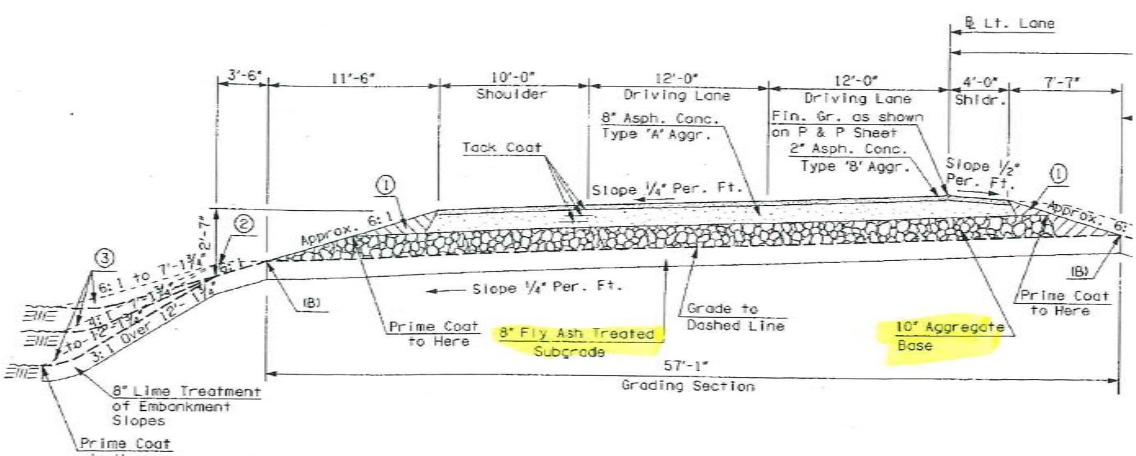


Figure 85. Typical cross section

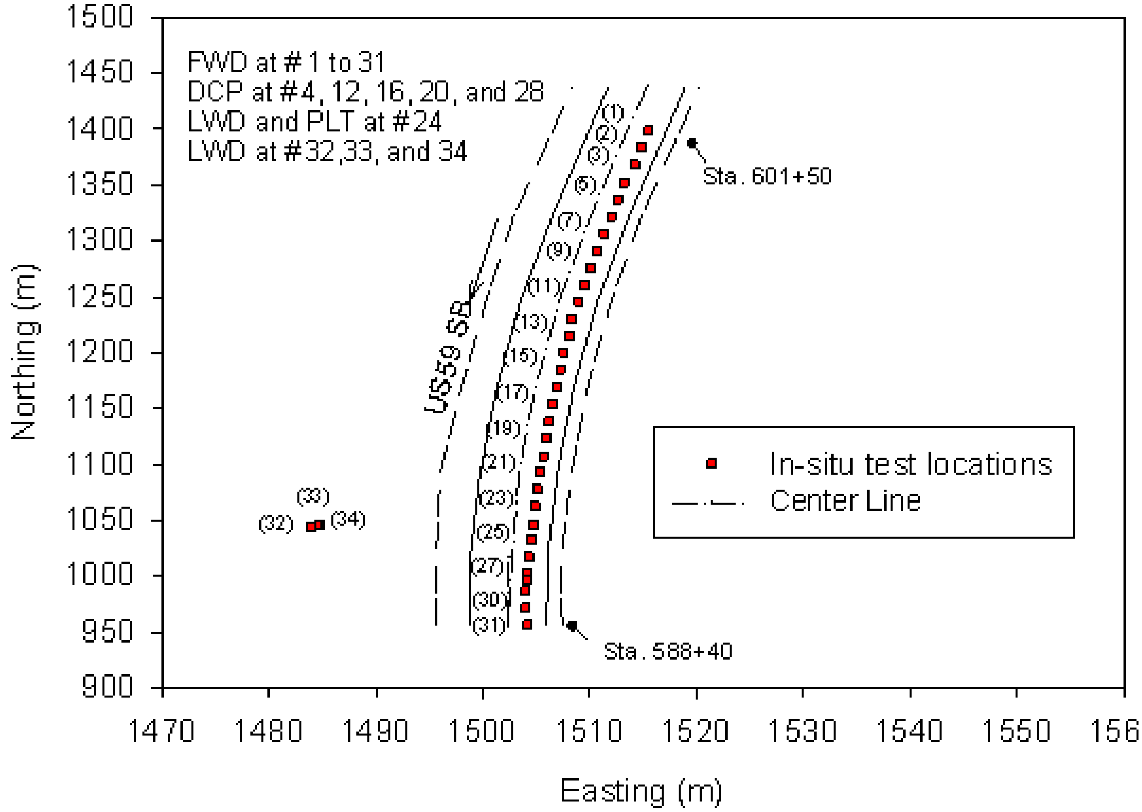


Figure 86. Test section plan layout

Figure 87. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The base and stabilized subgrade samples were taken at test point 24. The natural subgrade sample was taken at test point 32. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4 (0), and the top 100 mm (4 in.) stabilized subgrade was classified as SM and A-4 (0). Table 28 provides material properties of base and subgrade layer. After treatment, the gravel content increased from about 7.2% to 16.1%, and the sand content increased from about 30.5% to 48.2%. The clay content decreased from about 28.2 % to 4.2%, and the silt content decreased from about 37.7% to about 31.5%. LL values of stabilized subgrade samples were changed to about 33%. PI value was 6 for stabilized subgrade and 25 for natural subgrade. Figure 88 shows the soil type of subgrade has been modified after treatment. In-situ density and moisture content of some test points were recorded during construction shown in Appendix G.

Table 28. Summary of material properties

Parameter	**US 59 OK**		
Material Description	Base	Stabilized Subgrade	Natural Subgrade
Depth mm (in.)	0-254 (0-10)	0-200 (0-8)	—
Gravel Content (%) (> 4.75mm)	49.7	16.1	3.6
Sand Content (%) (4.75mm – 75µm)	31.1	48.2	30.5
Silt Content (%) (75µm – 2µm)	15.2	31.5	37.7
Clay Content (%) (< 2µm)	4.0	4.2	28.2
Coefficient of Uniformity (C_u)	446.7	110.3	—
Coefficient of Curvature (C_c)	5.2	0.4	—
Liquid Limit, LL (%)	24.7	32.7	45.9
Plasticity Index, PI	9.7	5.6	24.7
AASHTO	A-1-b	A-4	A-4
USCS	GM	SM	ML
Water Content (%)	5.0	17.7	13.2

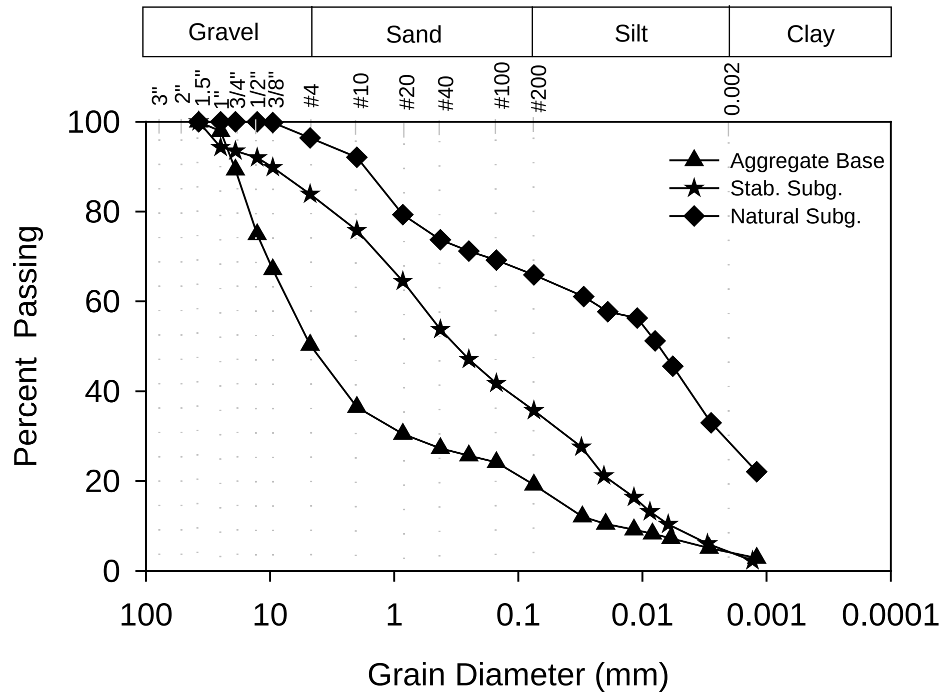


Figure 88. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Table 29 provides pH values of natural and stabilized subgrade. The pH value was 4.8 for natural subgrade and 8.9 for stabilized subgrade.

Table 29. Summary of pH value of subgrade

Depth	pH value
Natural subgrade	4.8
Fly ash stabilized subgrade	8.9

SEM Analysis

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 89. The majority elements were calcium (Ca), silica (Si), alumina (Al), and oxygen (O). Additional present elements were iron (Fe), potassium (K), and Sodium (Na).

Figure 90 compares element concentration in Al, Si, O, S, Mg, Ca, K, and C for the stabilized subgrade sample in area a and b. The sample shows high concentration of Si, Al, and O in both areas a and b, and low concentration of Ca in area a. All SEM images are presented in Figure 91 and Appendix D.

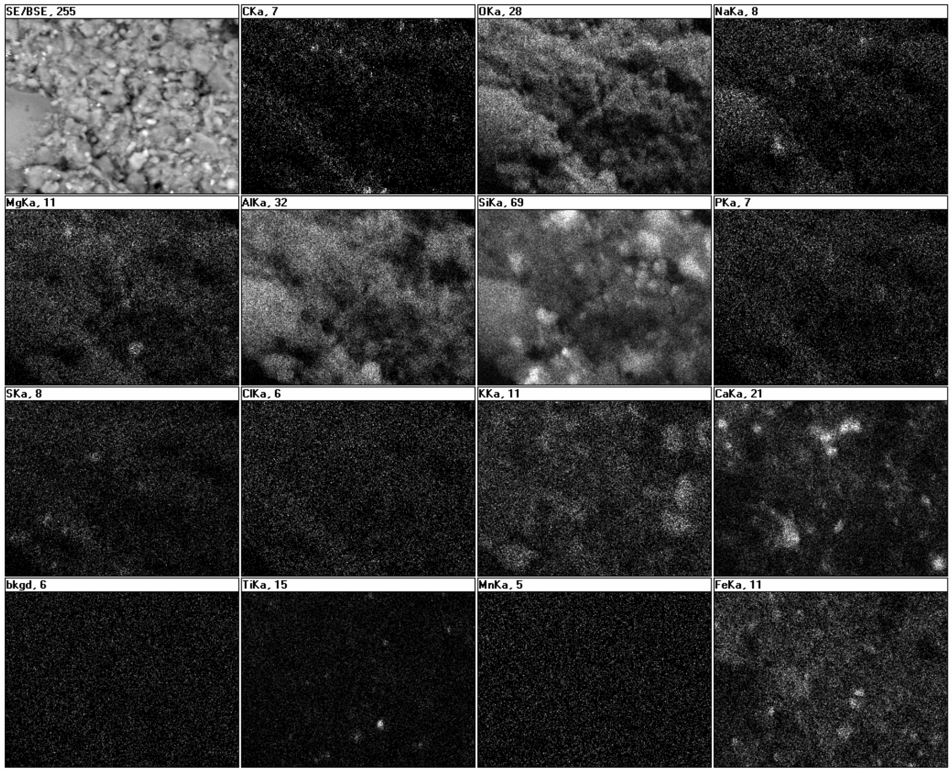


Figure 89. EDS map of stabilized subgrade sample (1500 ×)

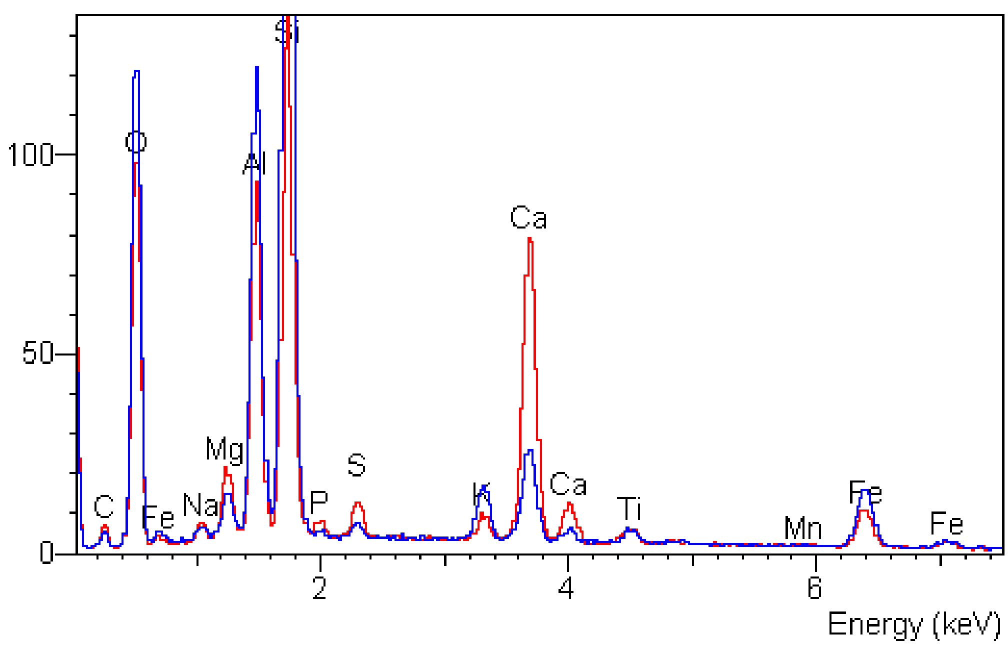


Figure 90. EDS intensity counts for stabilized subgrade sample in area a (blue line: 500×) and stabilized subgrade sample in area b (red line: 500×)

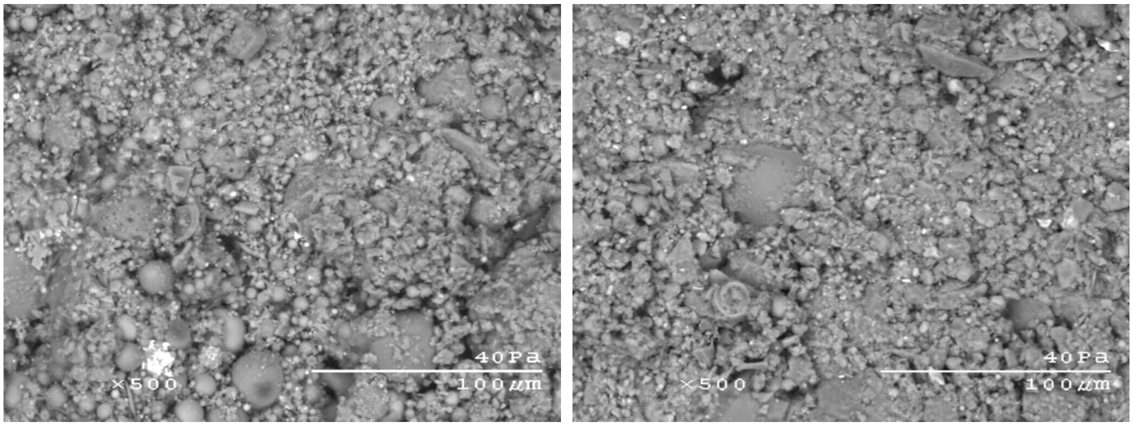


Figure 91. SEM of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP profiles and cumulative drops versus CBR are shown in Figure 92. Average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 93. The major observations: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 139%, (2) the average CBR of the natural subgrade was 23%, (3) the CBR of the stabilized subgrade was 640% of the natural subgrade, (4) the bottom layer of stabilized subgrade has a lower CBR than the top layer, and (5) from DCP profiles, the actual average treatment thickness was about 150 mm (6 in.), which was thinner the design value of 200 mm (8 in).

Backcalculated subgrade elastic moduli (E_{FWD}) and deflections (D_0) were presented in Figure 94. In the backcalculation, the average applied test load was 57 KN (12906 lb). The assumptions of poison's ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, aggregate base, stabilized subgrade and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. The middle depth of ACC pavement was measured as 18 ^{0}C (65 ^{0}F). Deflections under the loading plate (D_0) were adjusted to a standard temperature of 20 ^{0}C (68 ^{0}F) using equation (5). The key findings are:

- The average corrected D_0 was about 0.20 mm under average applied load of 57 KN (12906 lb). As corrected D_0 decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 383 MPa for natural subgrade and increased to 819 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 230% of the natural subgrade.
- The values of E_{FWD} of stabilized and natural subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 95 presents the stress-strain relationship at point 24. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 96. The correction of k′u was made using the curve in Figure 8. The LWD elastic modulus (E_{LWD}) of stabilized subgrade was equal to 0.6 E_{V1} and 0.4 E_{V2}. The E_{LWD} of stabilized subgrade was $0.1E_{FWD.}$ Table 31 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 32. All in-situ test results are presented in Appendix F.

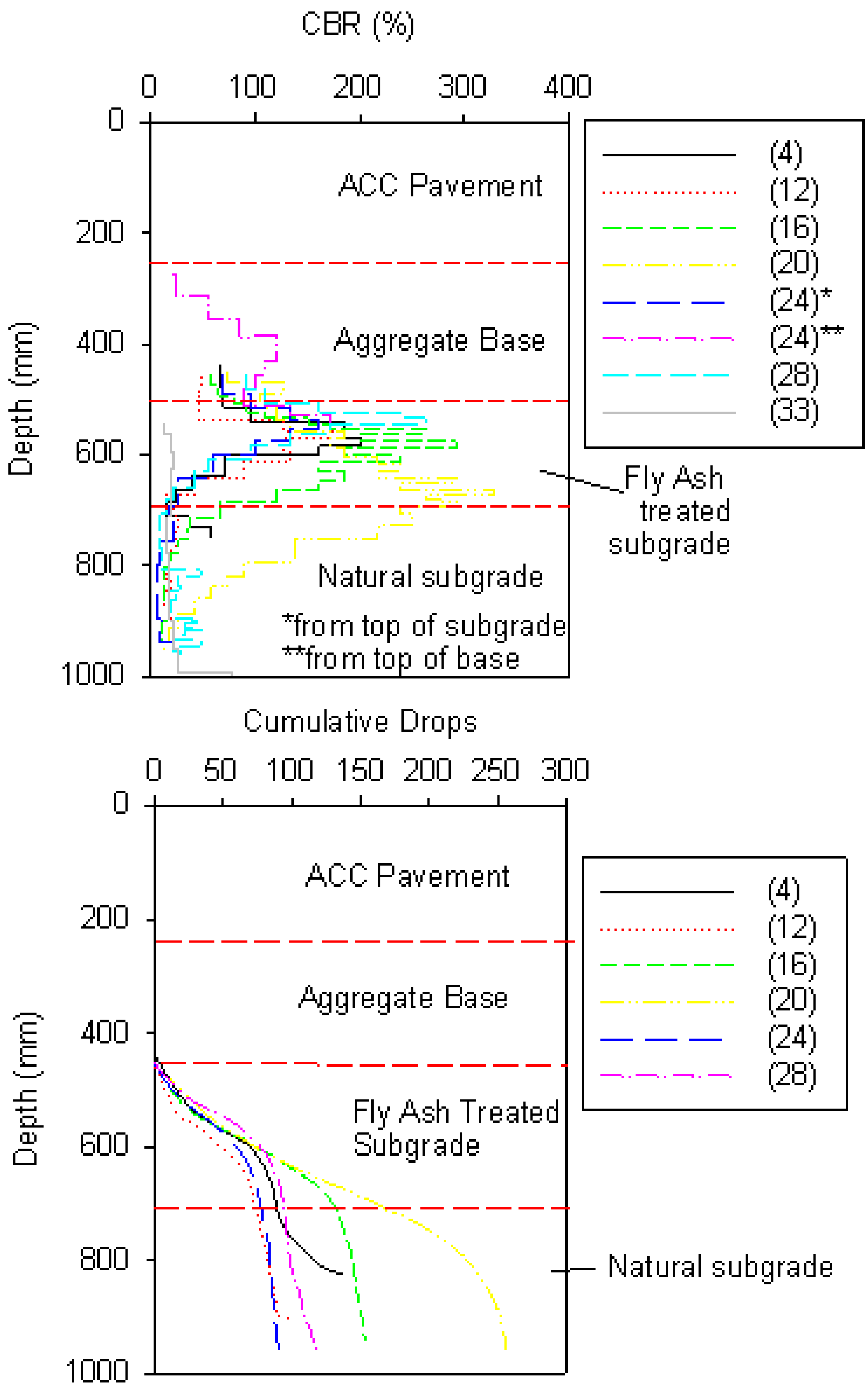


Figure 92. CBR – DCP profile and cumulative drops versus CBR of test points

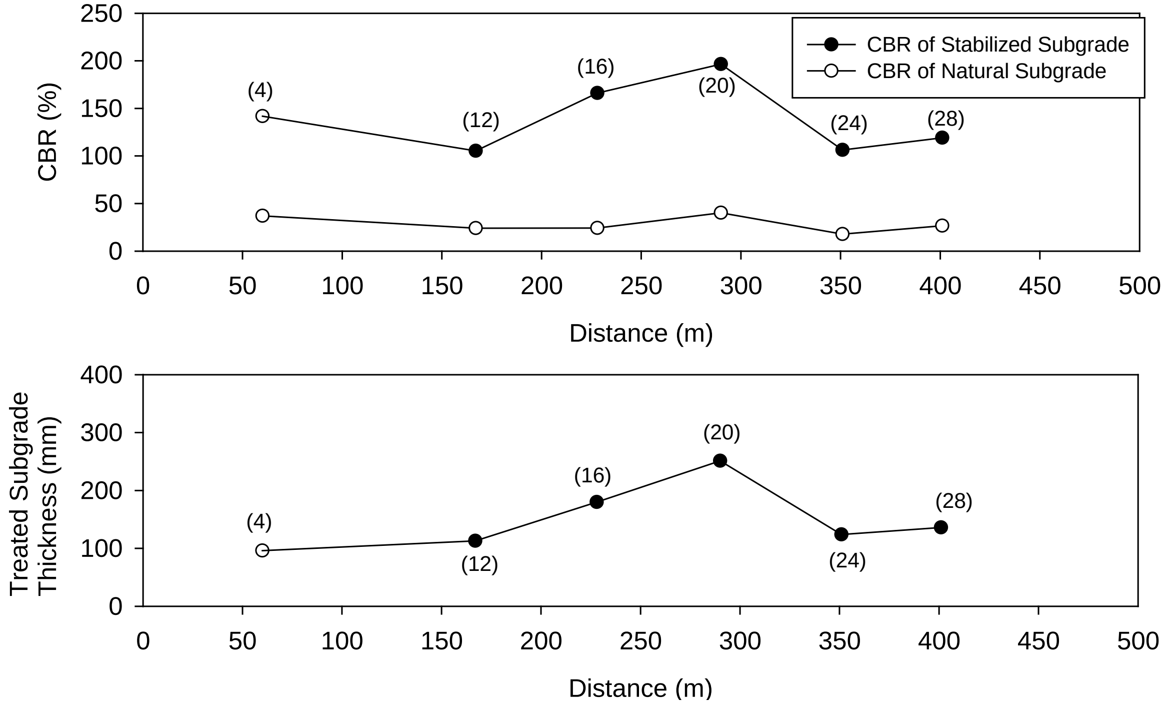


Figure 93. CBR and stabilized subgrade thickness from CBR-DCP profile

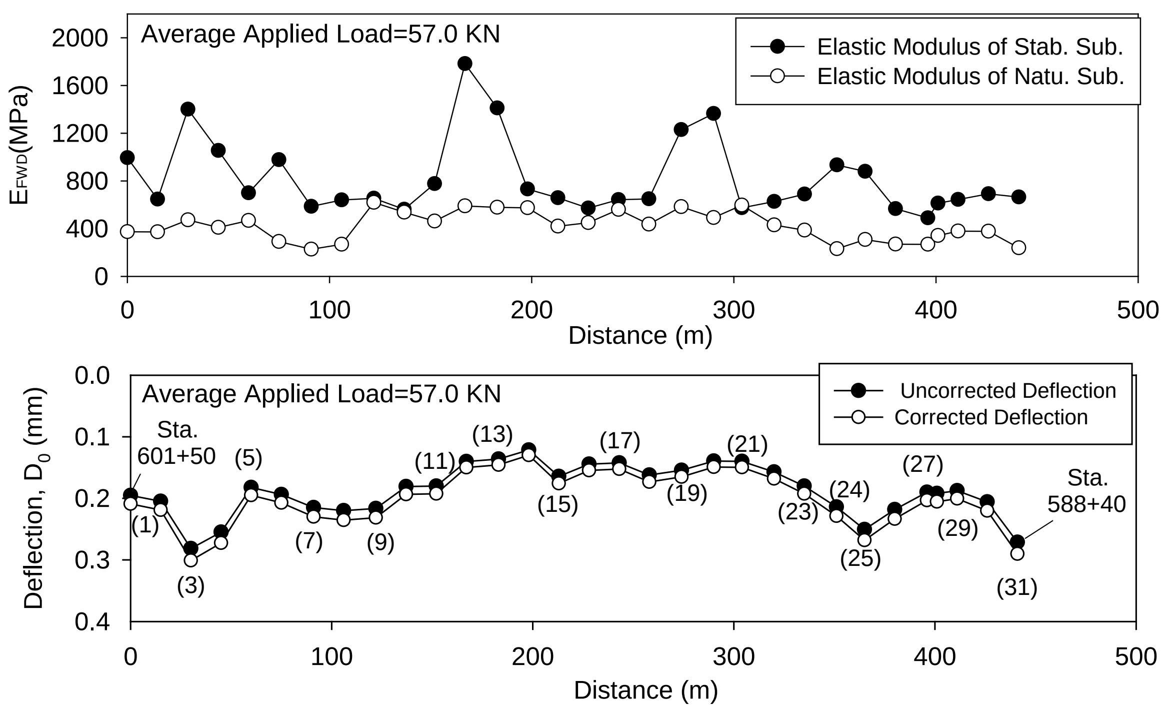


Figure 94. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

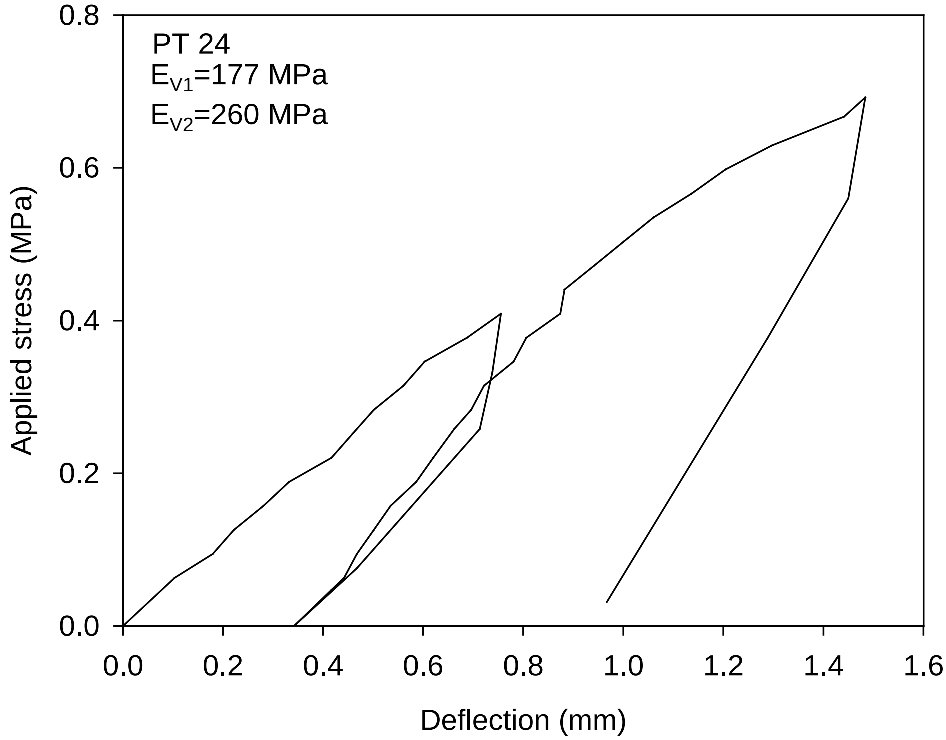


Figure 95. Stress – strain curves from plate load test at point 24

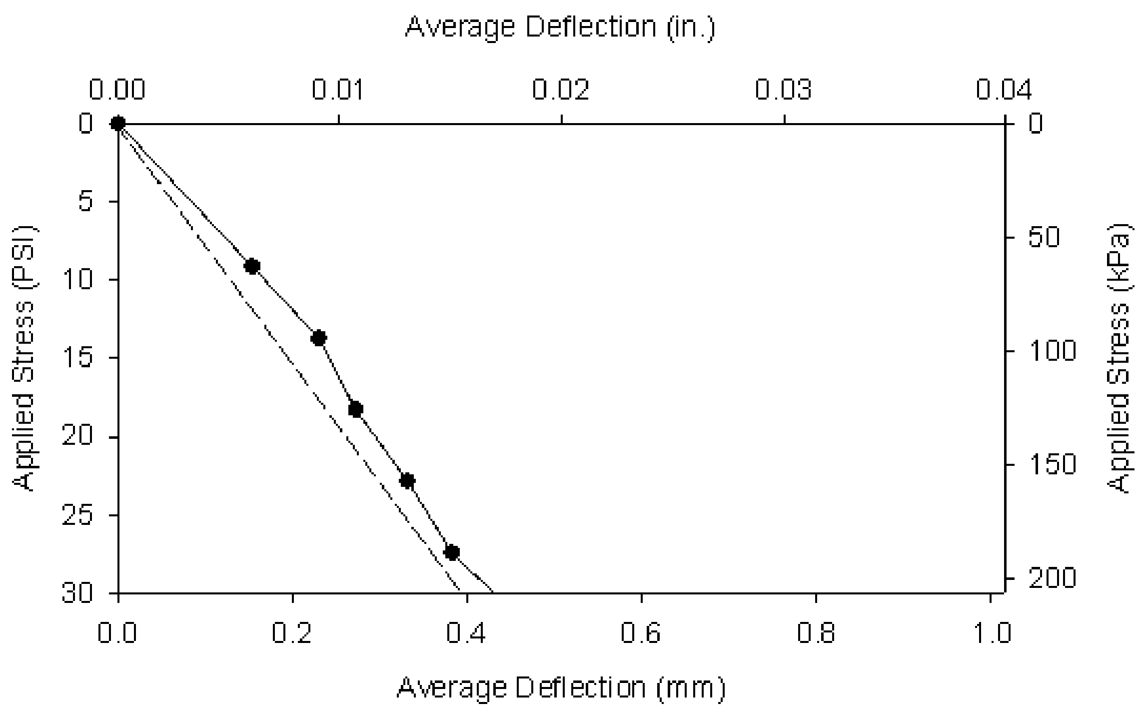


Figure 96. Stress – strain curves for obtaining K_U at point 24

Table 30. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
24	Base	Top of base	126	126
24	Stabilized Subgrade	Top of stabilized subgrade	105	105
32	Natural Subgrade	Top of natural subgrade	26	20
33	Natural Subgrade	Top of natural subgrade	13	
34	Natural Subgrade	Top of natural subgrade	20	

Table 31. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio		
CBR	E_{FWD}	E_{LWD}
6.4	2.3	5.3

Table 32. Summary statistics of test results from in-situ testing

Statistic	Base	Stabilized Subgrade							Natural Subgrade		
Meas.	E_{LWD}	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	Thi.	CBR	E_{FWD}	E_{LWD}
	MPa	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	MPa
Number of Meas. (n)	1	6	31	1	1	1	1	6	6	31	3
Mean Value (μ)	126	139	819	105	177	261	164	150	23	383	20
Standard Deviation (σ)	—	36	316	—	—	—	—	57	—	110	8
Coefficient of Variation COV (%)	—	26	39	—	—	—	—	38	—	29	33

US 75 SB, KS

Site Description

This project was located on the south bound of US 75 near south of Lyndon, in Osage County, Kansas. The general location of this site is shown in Figure 97. This road is a two-lane U.S. Highway, and was constructed in 1995. The length of this test section is approximately 700 m (2297 ft).The designed pavement consisted of a 330 mm (13 in.) thick asphalt concrete (AC), 50 mm (2 in.) thick base, and 100 mm (4 in.) lime stabilized subgrade. The subgrade was stabilized with 5% lime. ISU research team conducted in-situ testing near the milepost 123 on November 2, 2010 with assistance and traffic control provided by Kansas DOT.

The plan view of in-situ test locations is shown in Figure 98. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 10 m from points 1 to 30 and 20 m from points 31 to 50. DCP were conducted at test points 4, 11, 20, 28, 34, and 45. After coring, LWD was performed at different depths of stabilized subgrade, and PLT were performed on the top of stabilized subgrade at test point 18. Bag samples of subgrade were collected at test point 18 from the top to a depth of 250 mm (10 in.) subgrade at intervals about 50 mm (2 in.). Undisturbed Shelby tube samples were collected at test point 18 from the top of subgrade to a depth of 990 mm (39 in.) subgrade. Bag and Shelby tube samples were carefully sealed and transported to ISU laboratory.

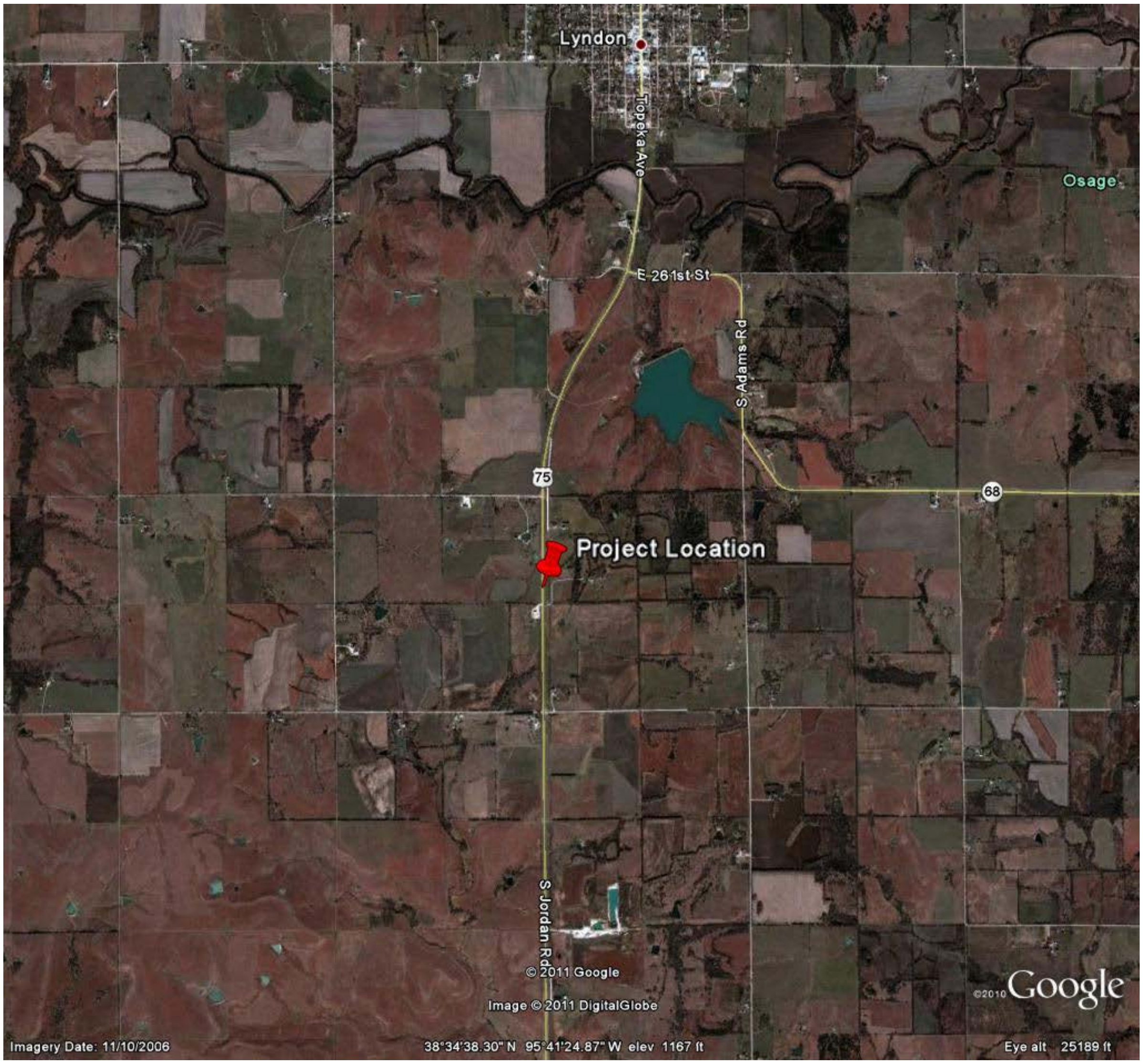


Figure 97. Project location of US 75 SB

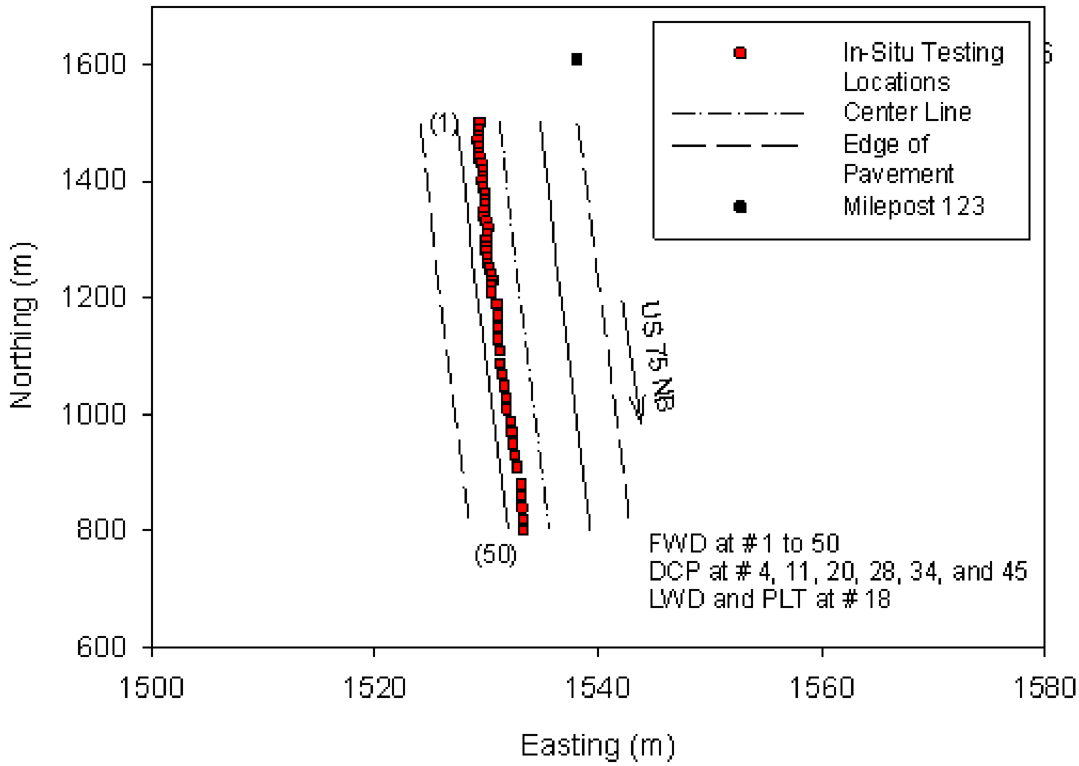


Figure 98. Test section plan layout

Figure 99. Site overview

Test Results and Analysis

Material Properties of Base and Subgrade

The stabilized subgrade samples were taken at test point 18 from the top to a depth of 250 mm (10 in.) subgrade at intervals of about 50 mm (2 in.). The natural subgrade sample was collected from Shelby tube at test point 18. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4, and the top 50 mm (2 in.) stabilized subgrade was classified as SM and A-2. The bottom 50-100 mm (2-4 in.) stabilized subgrade soil was classified as ML and A-4 as same as the soil type of natural subgrade. Table 33 provides material properties of subgrade, and it is shown that gravel, sand, silt, and clay content were largely different between natural subgrade and the top 50 mm (2 in.) stabilized subgrade. The average LL values of natural and stabilized subgrade samples were approximately equal. The average PI values of the top 50 mm (2 in.) stabilized subgrade samples were about 19 smaller than natural subgrade. PI values of the bottom 50 mm (2 in.) stabilized subgrade samples were about 5 smaller than natural subgrade. Figure 100 shows particle size distribution curves of different subgrade layers. Test results show the soil type of subgrade has been modified after treatment.

Table 33. Summary of material properties

Parameter	**US 75 SB KS**					
Material Description	Natural Sub.	Base	Stab. Sub.	Stab. Sub.	Sub.	Sub.
Depth mm (in.)	838-990 (33-39)	0-50 (0-2)	0-50 (0-2)	50-100 (2-4)	100-150 (4-6)	150-250 (6-10)
Gravel (%) (> 4.75mm)	0.4	48.3	22.5	11.4	1.0	0.4
Sand (%) (4.75mm – 75µm)	2.9	40.2	51.9	25.2	7.6	4.7
Silt (%) (75µm – 2µm)	30.3	8.9	19.9	36.7	51.1	55.6
Clay (%) (< 2µm)	66.4	2.6	5.7	26.7	40.3	39.3
C_u	—	149.3	481.8	—	—	—
C_c	—	15.0	6.6	—	—	—
Liquid Limit, LL (%)	56.1	56.5	54.0	55.6	57.5	56.1
Plasticity Index, PI	33.1	13.9	14.0	28.3	34.8	33.0
AASHTO	A-4	A-1-a	A-2	A-4	A-4	A-4
USCS	ML	GP-GM	SM	ML	ML	ML
Water Content (%)	23.8	32.4	29.9	25.1	25.2	25.5

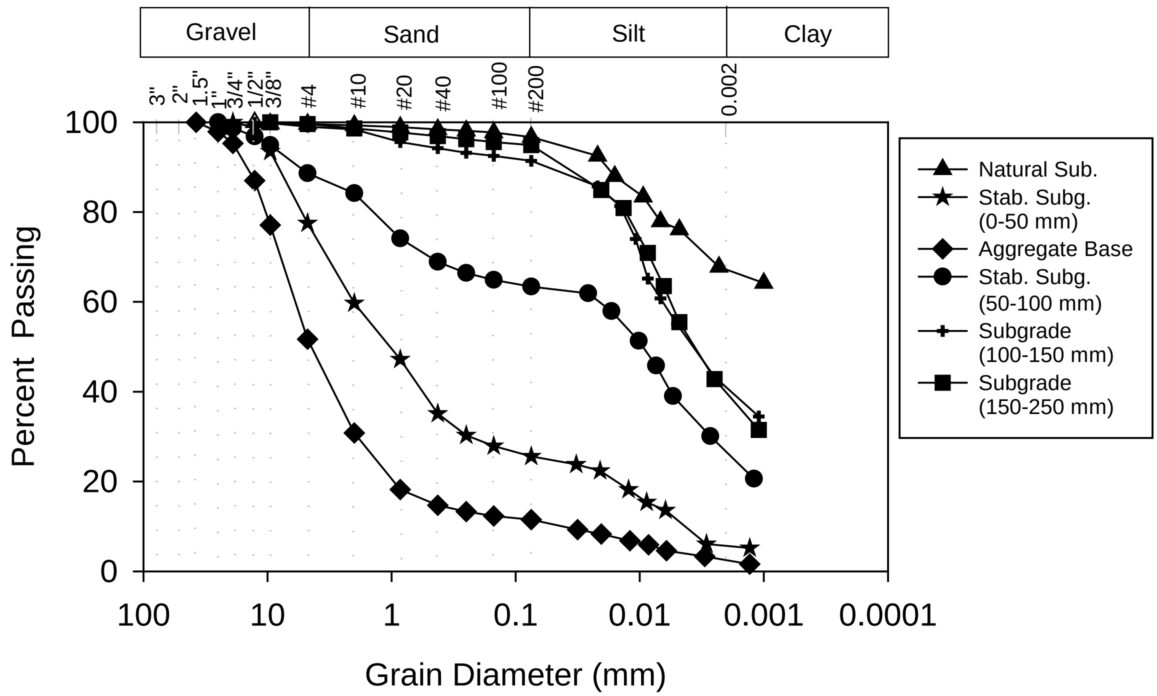


Figure 100. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Figure 101 shows the pH profile of subgrade at test point 8. The pH values of stabilized subgrade ranged from about 7.7 to 8.8. It gradually decreased from the top of stabilized subgrade to the bottom of stabilized subgrade. Below the stabilized subgrade, the pH values of subgrade keep constantly to a depth of 400 mm. Then the pH value starts to decrease from the value of 7.5 to 6.5 to a depth of 1000 mm. The pH values of stabilized subgrade ranged from about 6.5 to 8.0.

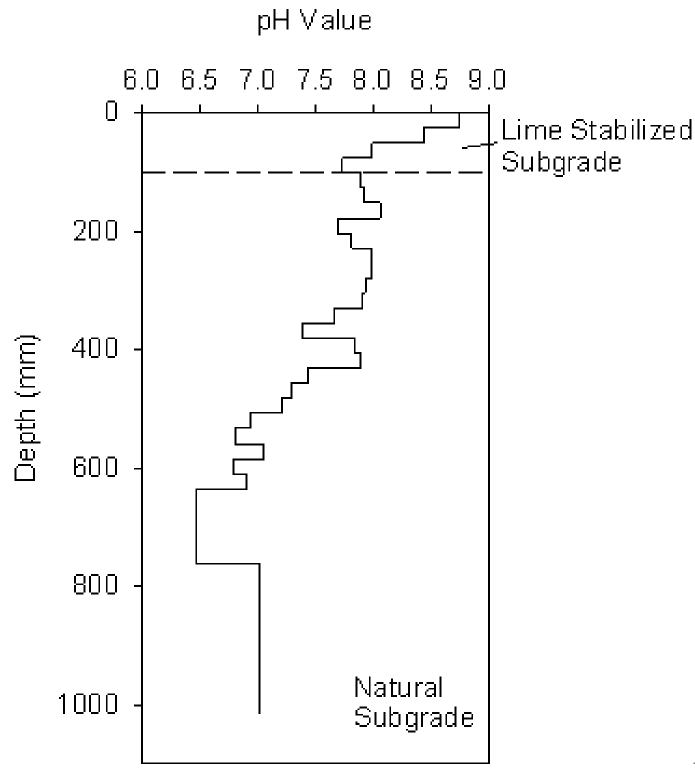


Figure 101. pH profile of subgrade

SEM Analysis

The energy dispersive spectrometry (EDS) map of natural subgrade is shown in Figure 102 and Figure 103. The majority elements were silica (Si), alumina (Al), and oxygen (O). Additional present elements were iron (Fe), potassium (Mg), and Sodium (Na).

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 103. The majority elements were calcium (Ca), Si, Al, phosphorus (P), and O. The mineral Ca enriched only in a small area. Additional present elements were Fe, potassium (K) and Na.

Figure 104, Figure 105, and Figure 106 compare element concentration in Al, Si, O, S, Mg, Ca, K, P, and C for natural and stabilized subgrade samples. The natural subgrade sample shows less concentration of Ca and P, and higher concentration of Si, Al, and O. The stabilized subgrade sample at 30 × and 150 × magnifications shows much less concentration of Ca and P than that sample at 1500 × magnification. All SEM images are presented in Figure 107, Figure 108, and Appendix D.

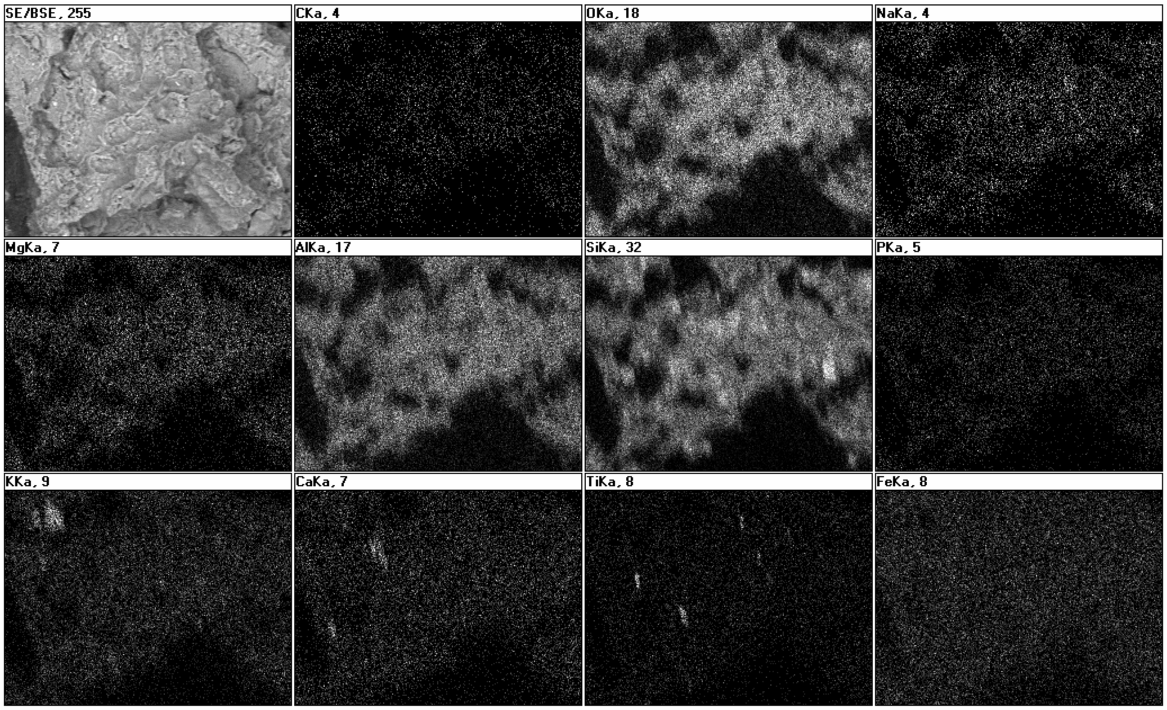


Figure 102. EDS map of natural subgrade sample (500 ×)

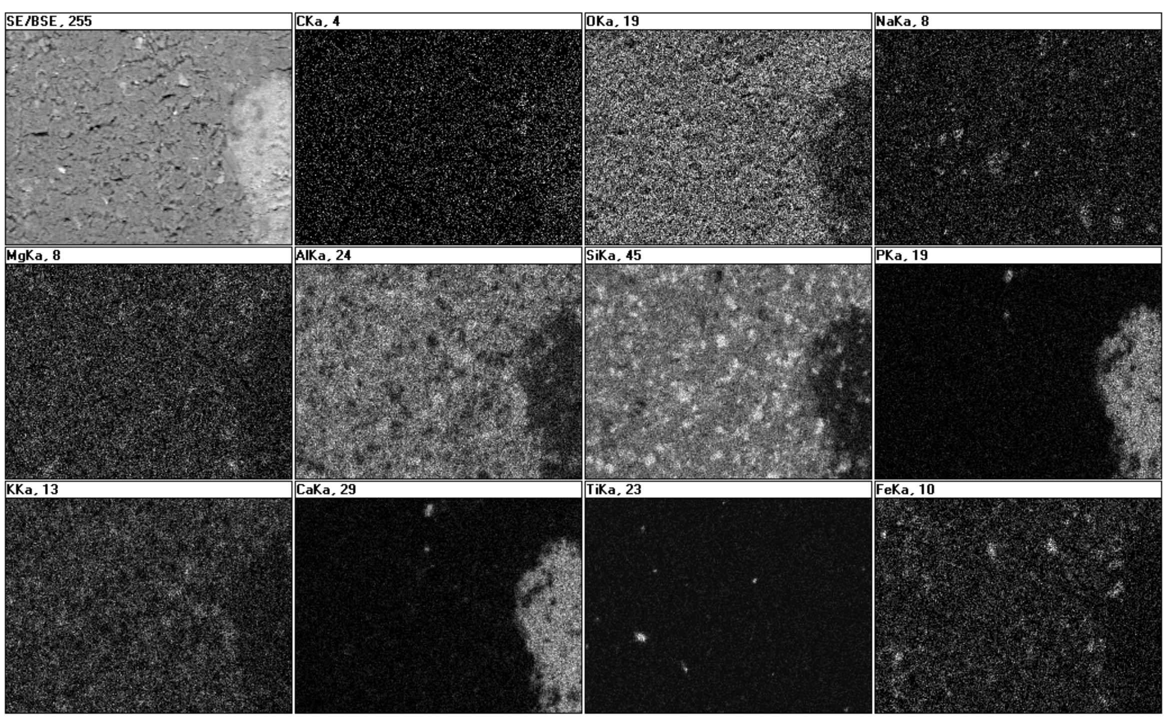


Figure 103. EDS map of stabilized subgrade sample (500 ×)

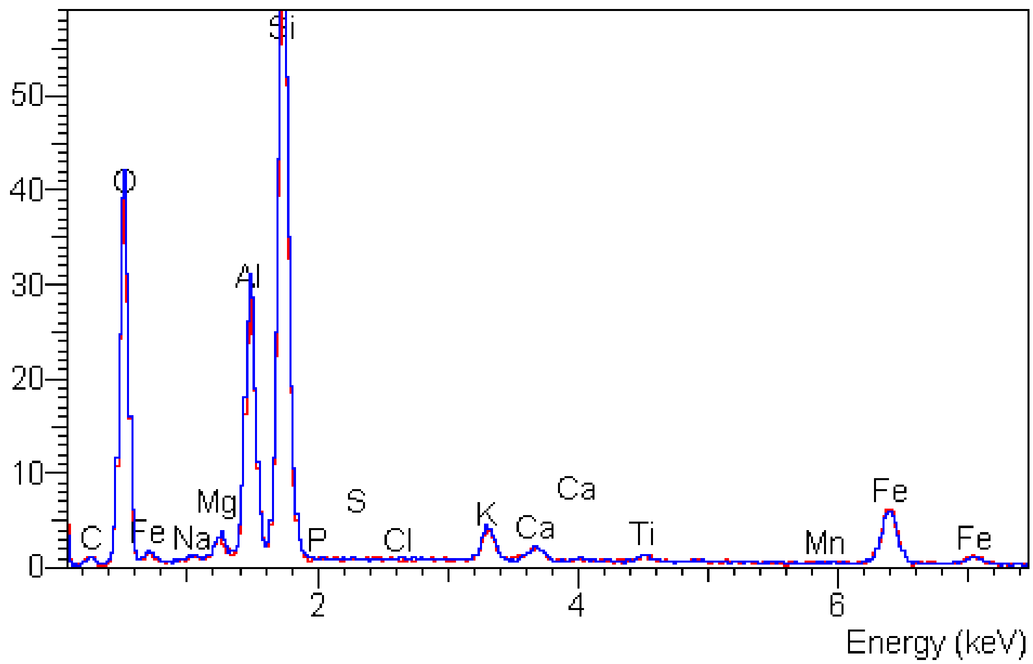


Figure 104. EDS intensity counts for natural subgrade sample (red line: 30×; blue line: 150×)

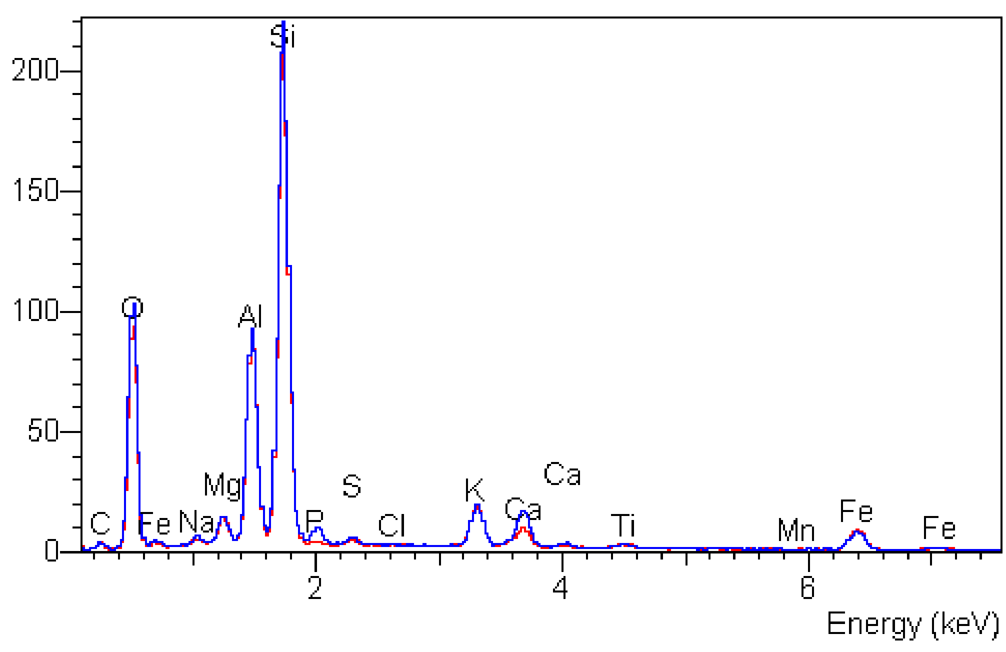


Figure 105. EDS intensity counts for stabilized subgrade sample (red line: 30×; blue line: 150×)

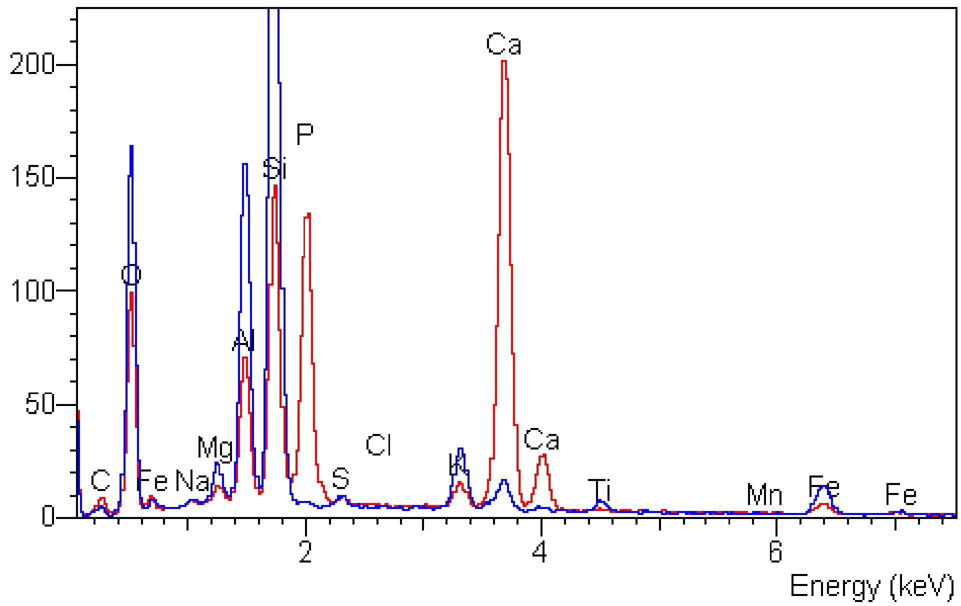


Figure 106. EDS intensity counts for stabilized subgrade sample in area a (red line: 1500×) and in area b (blue line: 1500×)

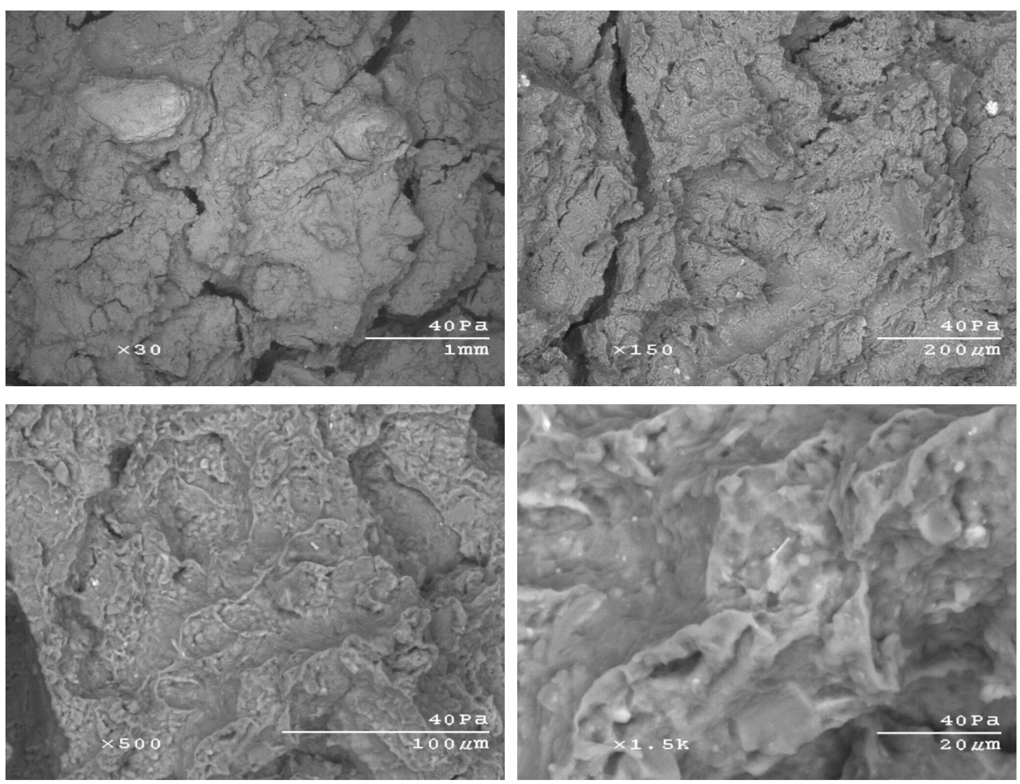


Figure 107. SEM images of natural subgrade

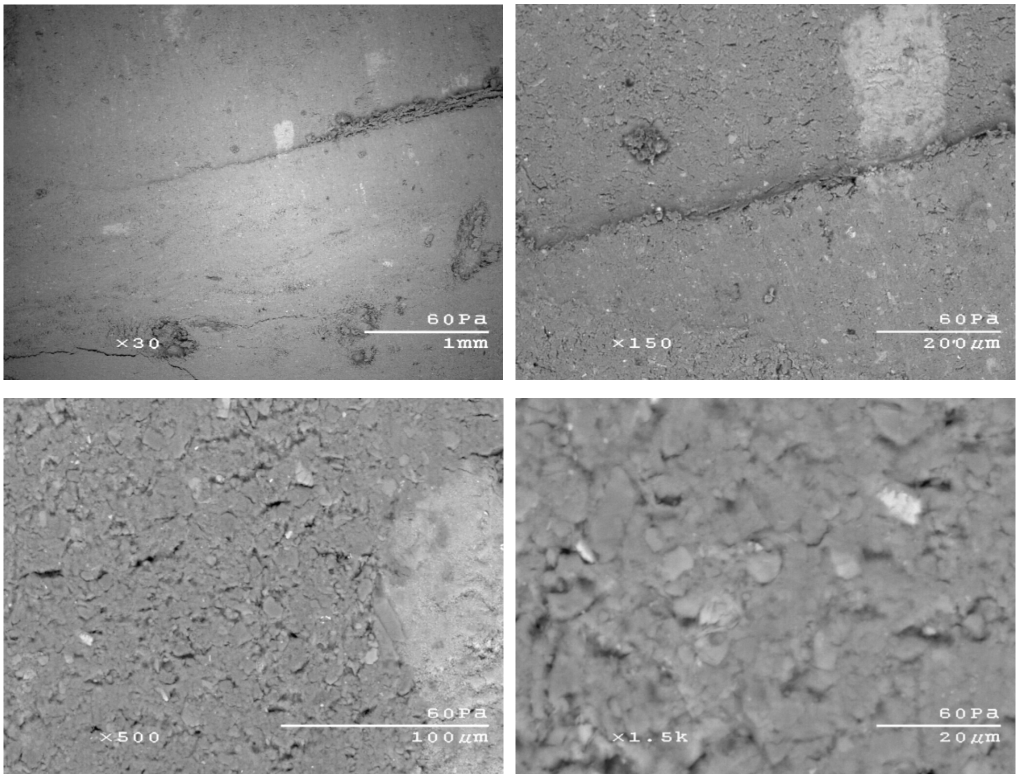


Figure 108. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP profiles and cumulative drops versus CBR are shown in Figure 109. Average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 110. The major observations are: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 30%, (2) the average CBR of the natural subgrade was 11%, (3) the average CBR of the stabilized subgrade was 270% of the natural subgrade, (4) the subgrade has not shown significantly strength improvement within the design thickness at test point 11, (5) the subgrade has shown slightly strength improvement at test points 20, 28, and 45, and (6) the effective treatment thickness was thinner than the design value.

Backcalculated subgrade elastic moduli (E_{FWD}) and surface deflections were presented in Figure 111. In the backcalculation, the applied test load was 57.9 KN (13020 lb). The assumptions of poison’s ratio were 0.35, 0.35, 0.40, and 0.40 for ACC surface layer, aggregate base, stabilized subgrade and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. Deflections under the loading plate were adjusted to a standard temperature of 20 ^{0}C (68 ^{0}F) using Equation (5). The temperature of middle depth of ACC pavement was measured as 9.8 ^{0}C (49.7 ^{0}F) prior to FWD testing. The key findings are:

- The average D_0 and $D_{0\text{-}cor}$ were about 0.13 mm and 0.19 mm under average applied load. As D_0 and $D_{0\text{-}cor}$ decrease, backcalculated E_{FWD} for both stabilized and natural subgrade increase.
- The average E_{FWD} was 323 MPa for natural subgrade and increased to 711 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 220% of natural subgrade.
- The values of E_{FWD} of natural and stabilized subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 112 presents the stress-strain relationship at point 18. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 113. The correction of k′u was made using the curve in Figure 8. The average E_{LWD} was 37 MPa for stabilized subgrade. The average E_{LWD} of stabilized subgrade was equal to 2.5 E_{V1} and 5.3 E_{V2}. The undrained shear strength (s_u) of the top subgrade (1-7 in.) has not showed strength improvement after treatment compared with underlying subgrade.

Table 34 lists all LWD test results. Table 35 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 36. All in-situ test results are presented in Appendix F.

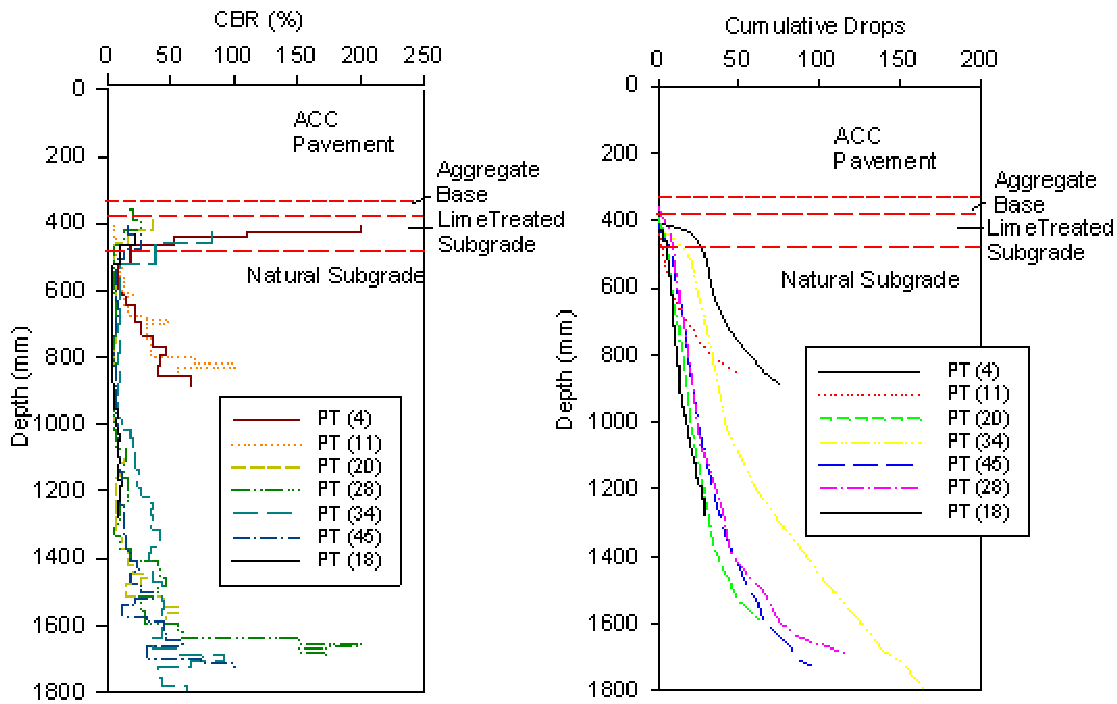


Figure 109. CBR – DCP profile of test points

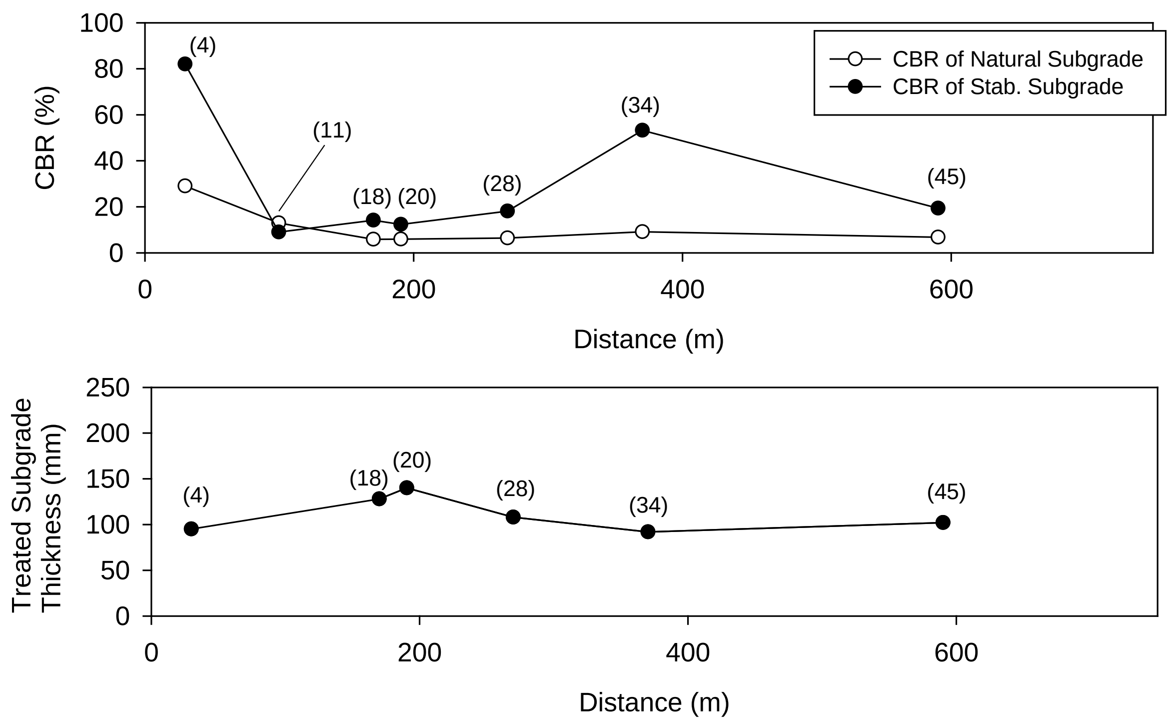


Figure 110. CBR of subgrade and stabilized subgrade thickness from DCP profile

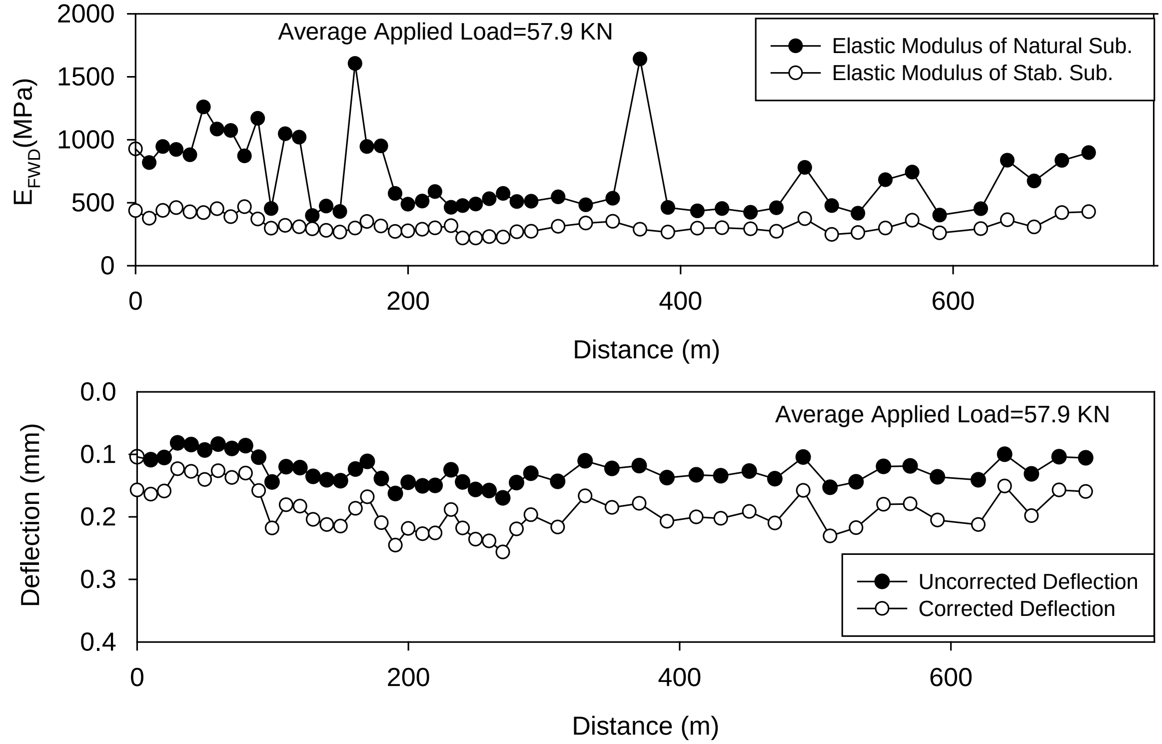


Figure 111. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

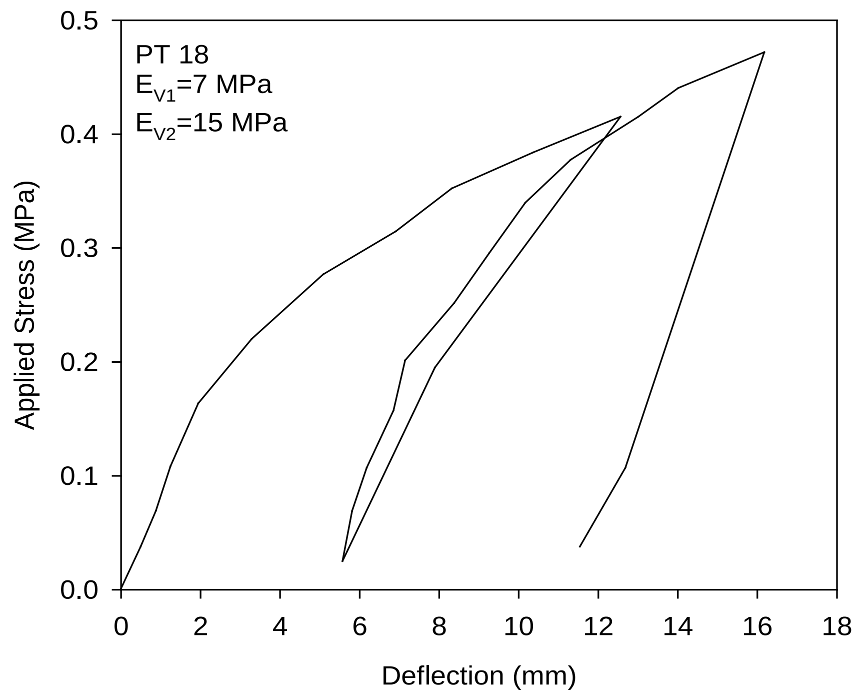


Figure 112. Corrected stress – strain curves from plate load test at point 18

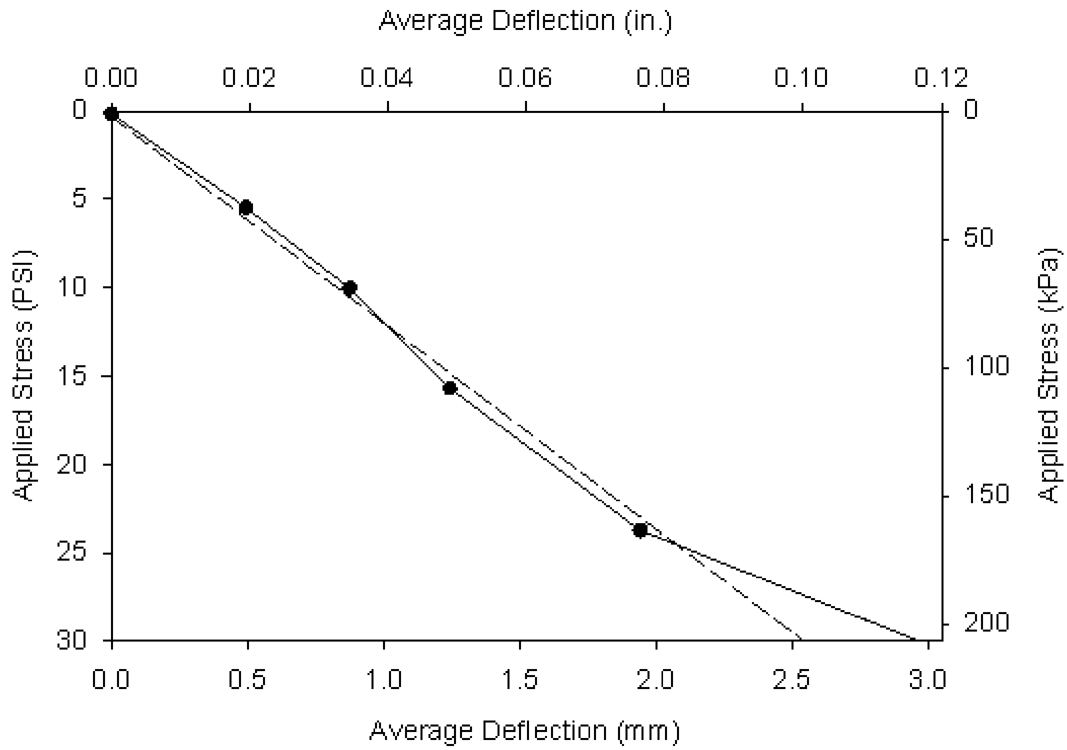


Figure 113. Stress – strain curves for obtaining K_U at point 18

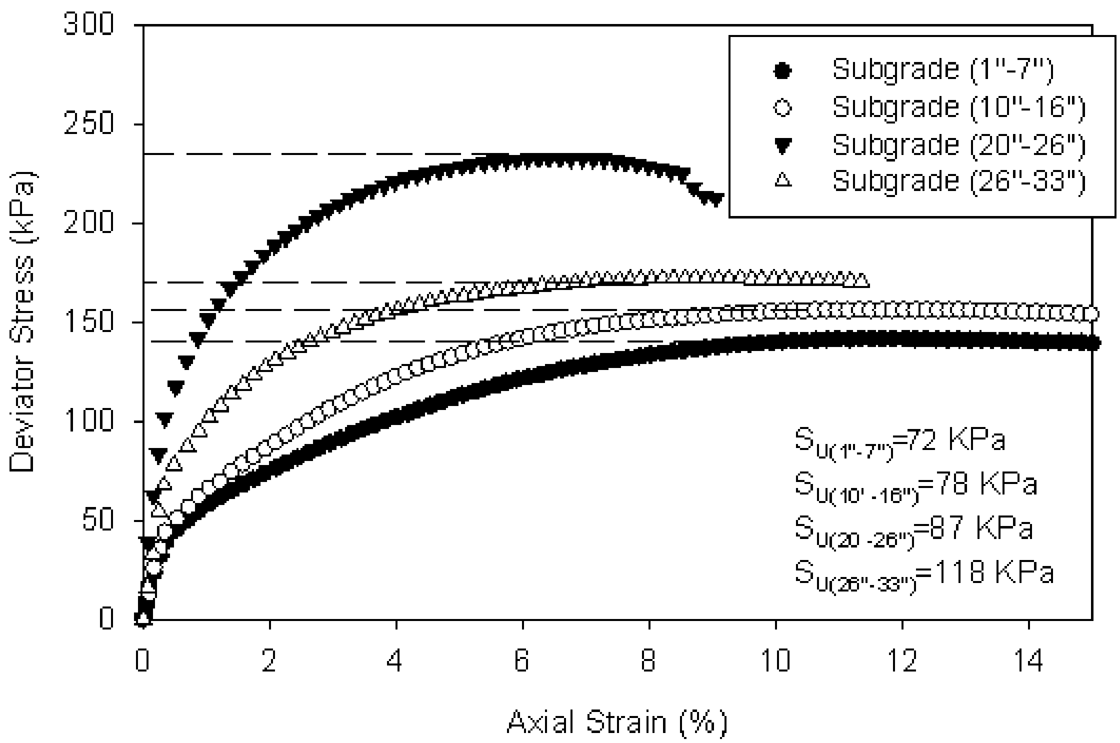


Figure 114. Unconsolidated – Undrained test of subgrade

Table 34. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
18	Stabilized subgrade	Top of stabilized subgrade	37	31
18	Stabilized subgrade	50 mm from top of stabilized subgrade	24	

Table 35. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio	
CBR	E_{FWD}
2.7	2.2

Table 36. Summary statistics of test results from in-situ testing

Statistic	Stabilized Subgrade							Natural Subgrade		FWD Def
Measurement	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	Thi.	CBR	E_{FWD}	$D_{0\text{-}Cor.}$
	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	mm
Number of Measurement(n)	7	50	2	1	1	1	6	7	50	50
Mean Value (μ)	30	711	31	7	15	31	111	11	323	0.19
Standard Deviation (σ)	28	304	18	—	—	—	19	8	68	0.03
Coefficient of Variation COV (%)	93	43	48	—	—	—	17	73	21	16

US 75 NB, KS

Site Description

This project was located on the south bound of US 75 NB near north of Hoyt, in Jackson County, Kansa. The general location of this site is shown in Figure 115. This road is a four-lane U.S. Highway. The road was constructed in 1995. The pavement consists of a 229 mm (9 in.) thick Portland cement concrete (PCC), 102 mm (4 in.) cement stabilized aggregate base, and 152 mm (6 in.) lime stabilized subgrade. The length of this test section is approximately 220 m (721 ft). ISU research team conducted in-situ testing near milepost 176 on November 3, 2010 with assistance and traffic control provided by Kansas DOT.

The plan view of in-situ test locations is shown in Figure 116. The research team preformed FWD tests on the surface of PCC pavement at center and joint of each slab. DCP were conducted at test points 3, 11, 31, 43, 49, and 51. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 25. Bag samples of subgrade were collected at test point 25. Natural subgrade samples were also collected at test point 51. Undisturbed Shelby tube samples were collected at test point 25 from the top to a depth of 330 mm (13 in.) subgrade.

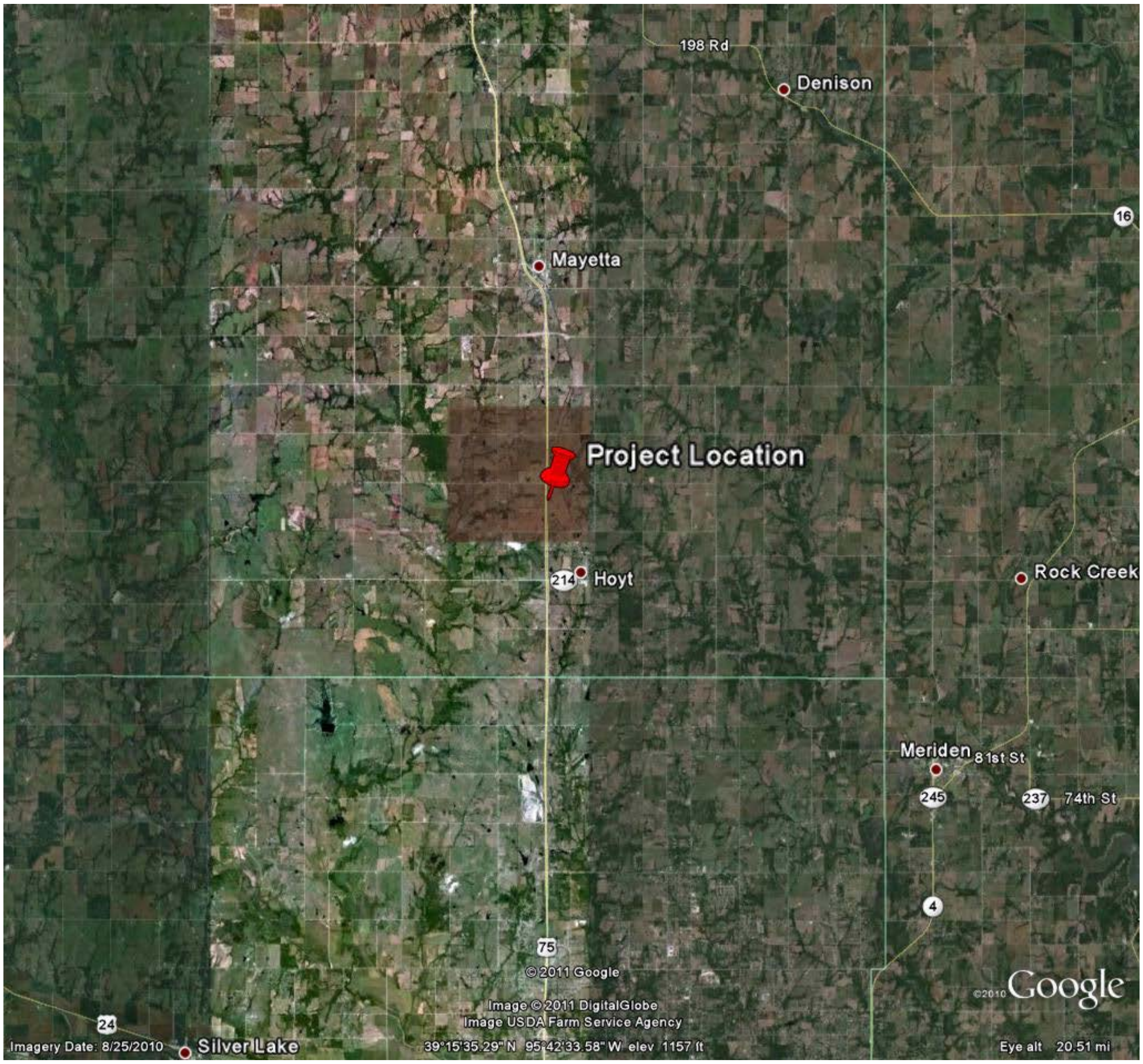


Figure 115. Project location of US 75 NB

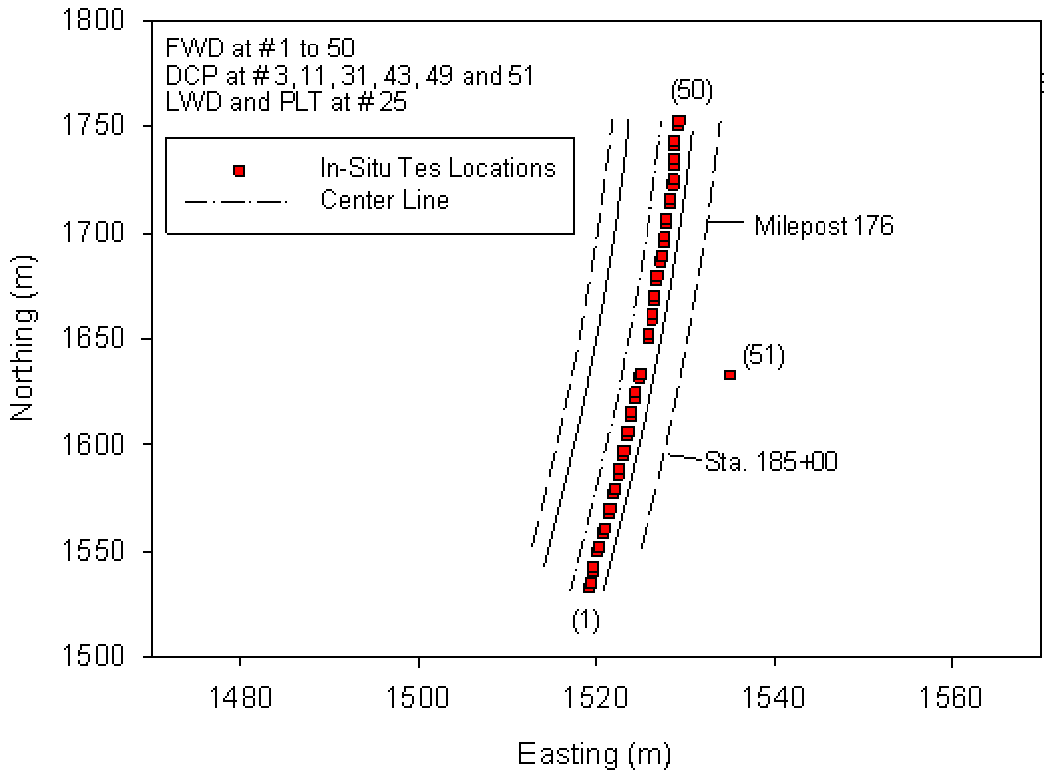


Figure 116. Test section plan layout

Figure 117. Site overview

Test Results and Analysis

Material Properties of Subgrade

The stabilized subgrade samples were taken at test point 25 from the top of subgrade to a depth of 150 mm (6 in.) at intervals of 50 mm (2 in.). The natural subgrade sample was collected at test point 51. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4; the stabilized subgrade was classified as SM and A-2-4 for the top 50 mm (2 in.) and A-2 for the depth from 50 mm to150 mm (2-6 in.). Table 37 provides material properties of subgrade. The average gravel content increased from about 2.6% for natural subgrade to 6.8% for stabilized subgrade, while the average sand content increased from about 28.5% to 58.6%. The average clay content decreased from about 32.6% to 6.2%, while the average silt content decreased from about 36.3% to about 28.4%. The average LL value was 45% stabilized subgrade and 52% for natural subgrade. The average PI value was 7.8 for stabilized subgrade and 34.3 for natural subgrade. The average moisture content was around 28.1% for the stabilized subgrade and 18.7% for the natural subgrade. Figure 118 shows particle size distribution curves of different subgrade layers. Test results show the soil type of subgrade has been modified after treatment.

Table 37. Summary of material properties

Parameter	**US 75 NB KS**				
Material Description	Natural Sub.	Base	Stab. Sub.	Stab. Sub.	Stab. Sub.
Depth mm (in.)	—	0-100 (0-4)	0-50 (0-2)	50-100 (2-4)	100-150 (4-6)
Gravel (%) (> 4.75mm)	2.6	60.4	8.5	4.9	7.1
Sand (%) (4.75mm – 75µm)	28.5	33.3	64.3	56.5	54.9
Silt (%) (75µm – 2µm)	36.3	5.1	19.5	33.4	32.3
Clay (%) (< 2µm)	32.6	1.2	7.7	5.2	5.7
C_u	—	20.4	165.3	65.3	67.8
C_c	—	3.0	6.4	0.6	0.5
Liquid Limit, LL (%)	52.0	36.5	44.0	45.3	45.8
Plasticity Index, PI	34.3	3.4	5.9	8.9	8.6
AASHTO	A-4	A-1-a	A-2-4	A-4	A-4
USCS	ML	GW-GM	SM	SM	SM
Water Content (%)	18.7	10.4	27.0	29.0	28.3

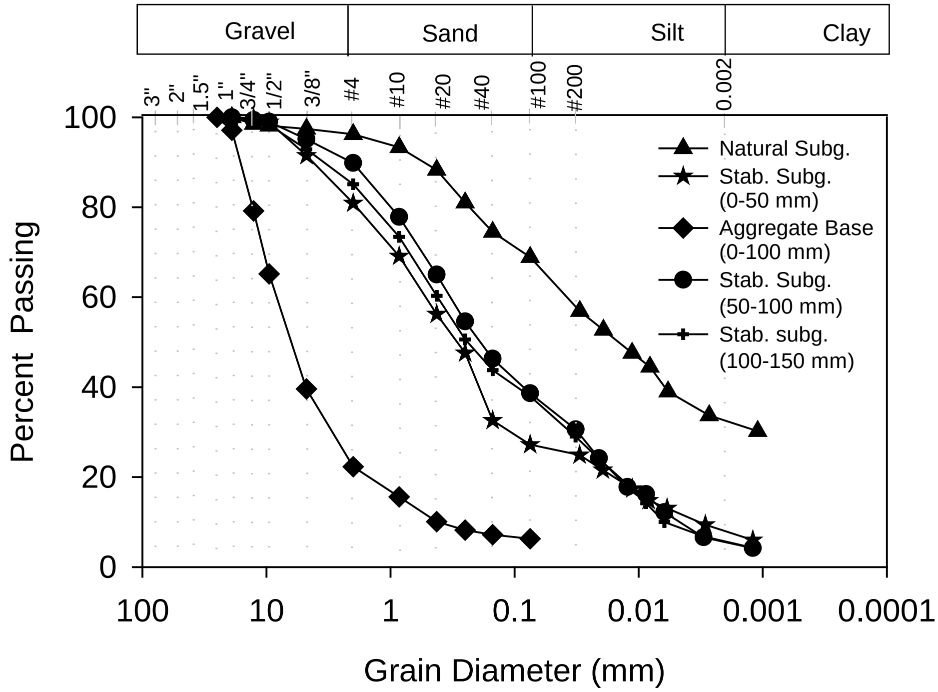


Figure 118. Particle size distribution curves for subgrade materials

pH of Stabilized and Natural Subgrade

Figure 119 shows the pH profile of subgrade at test point 25. The pH values of stabilized subgrade ranged from 8.7 to 9.4. It gradually decreased from the top of stabilized subgrade to the bottom of stabilized subgrade. The pH values of natural subgrade ranged from 7.9 to 8.1. It keeps constantly up a depth of 330 mm subgrade.

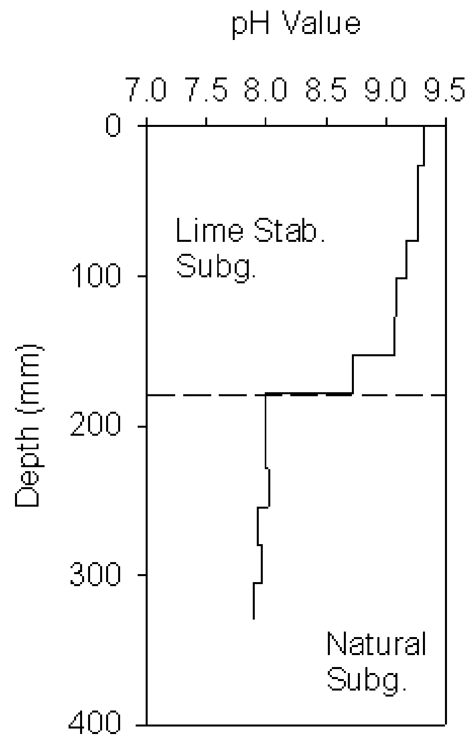


Figure 119. pH profile of subgrade

SEM Analysis

The energy dispersive spectrometry (EDS) map of natural subgrade is shown in Figure 120. The majority elements were silica (Si), alumina (Al), and oxygen (O). Additional present elements were potassium (K) and magnesium (Mg).

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 121. The majority elements were Si, Al, K, and O. The mineral calcium (Ca) was rarely presented. Additional present elements were iron (Fe), and Mg.

Figure 122 and Figure 123 compare element concentration in Al, Si, O, S, Mg, Ca, K, and C for stabilized and natural subgrade. The stabilized subgrade sample shows higher concentration of Ca and Fe than natural subgrade. All SEM images are presented in Figure 124, Figure 125, and Appendix D.

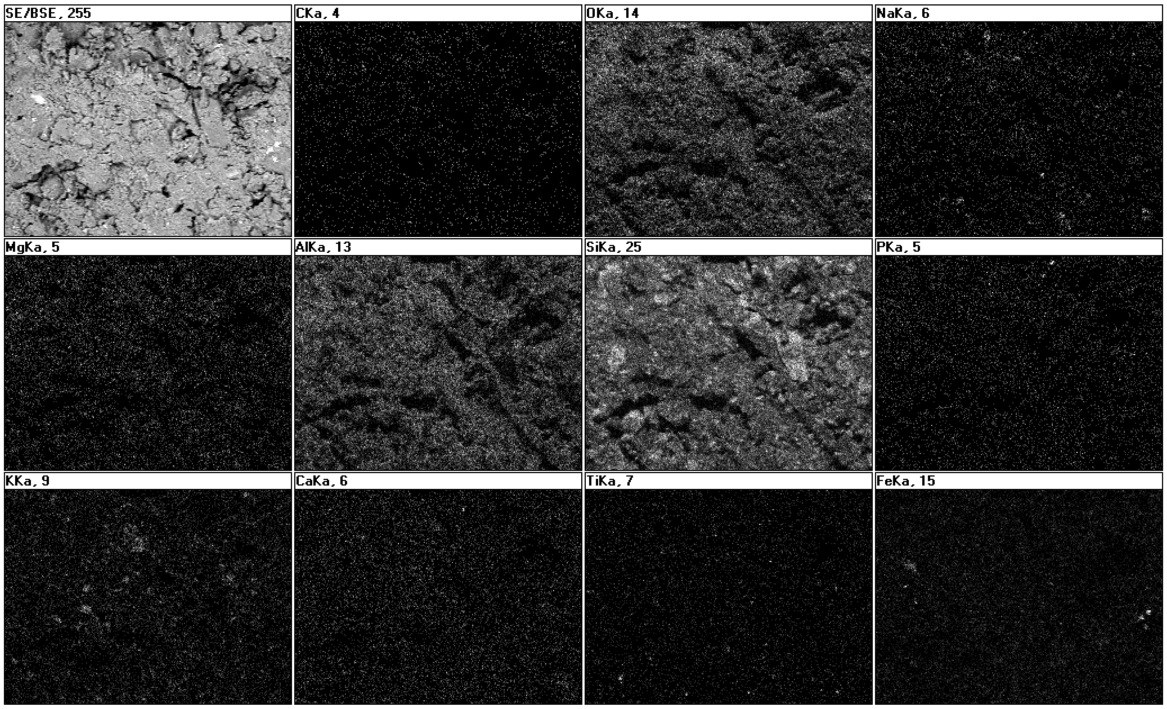


Figure 120. EDS map of natural subgrade sample (500 ×)

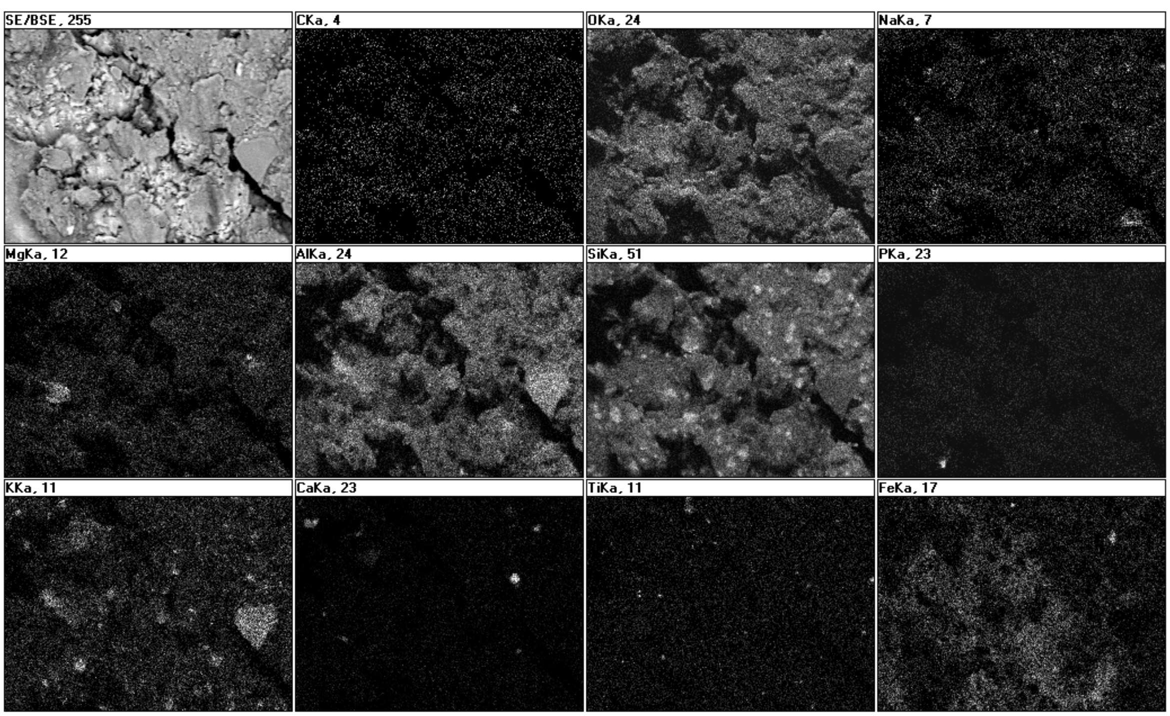


Figure 121. EDS map of stabilized subgrade sample (250 ×)

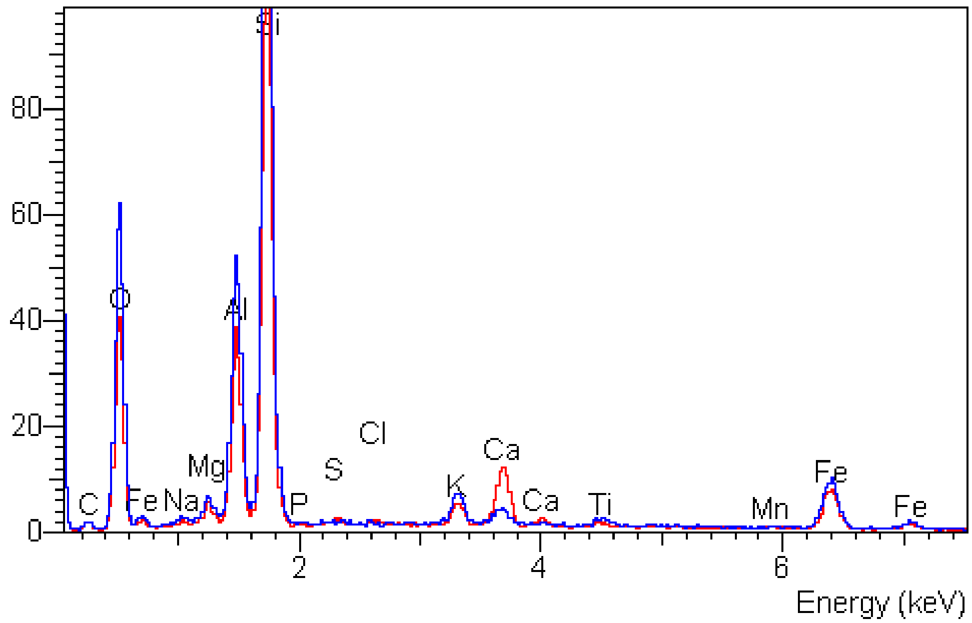


Figure 122. EDS intensity counts for stabilized subgrade sample (red line: 30×) and natural subgrade sample (blue line: 30×)

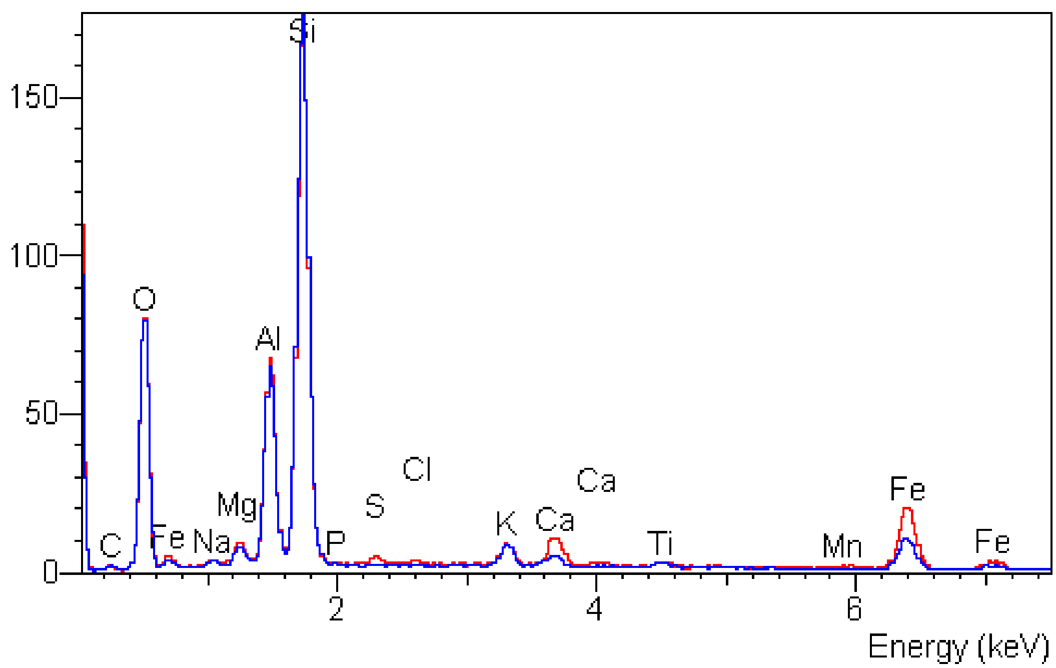


Figure 123. EDS intensity counts for stabilized subgrade sample (red line: 150×) and natural subgrade sample (blue line: 150×)

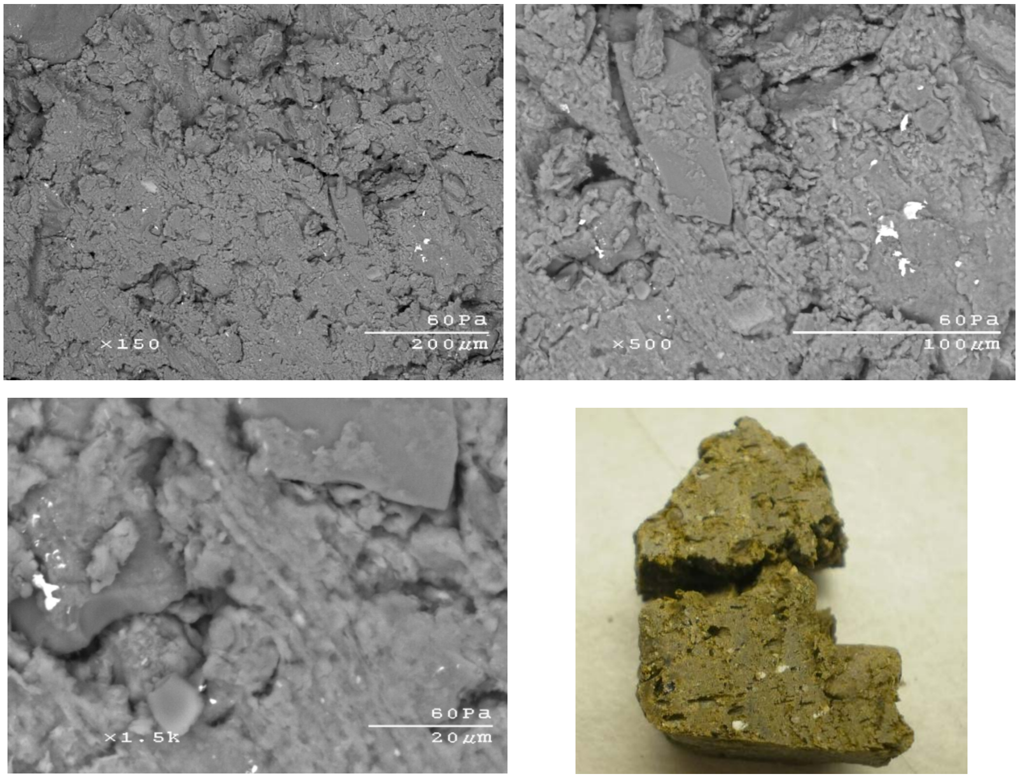


Figure 124. SEM images of natural subgrade

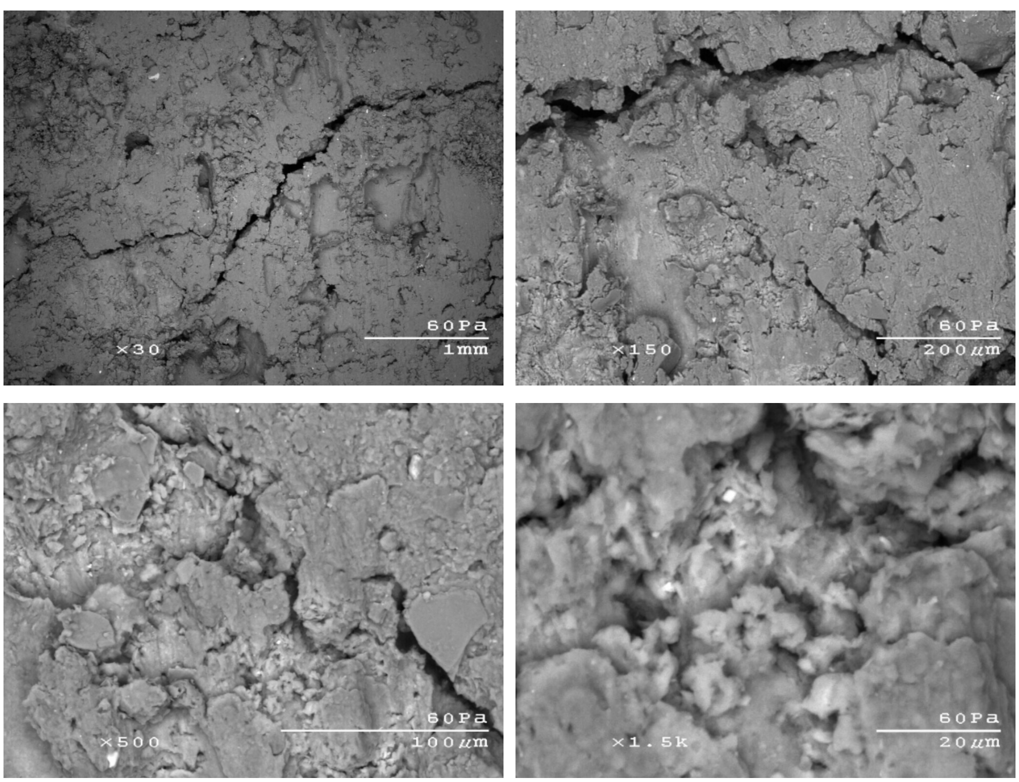


Figure 125. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP profiles and cumulative drops versus CBR are shown in Figure 126. The average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 127. The major observations are: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 20%, (2) the average CBR of the natural subgrade was 7%, (3) the average CBR of the stabilized subgrade was 290% of the natural subgrade, and (4) the actual average treatment thickness was about 128 mm (5 in.).

ERIDA assumes a two layers system for PCC pavement to calculate composite subgrade moduli (E_{sg}) and PCC pavement (E_{PCC}). Figure 128 shows subgrade moduli (E_{sg}) and deflection.

Figure 129 presents the stress-strain relationship at point 25. The values of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 130. The correction of k′u was made using the curve in Figure 8. The average LWD elastic modulus (E_{LWD}) was 25 MPa for stabilized subgrade and 15 MPa for natural subgrade. The average E_{LWD} of stabilized subgrade was equal to 0.3 E_{V1} and 0.2 E_{V2}.

Table 38 lists all LWD test results. Table 39 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results were listed in Table 40. All in-situ test results are presented in Appendix F.

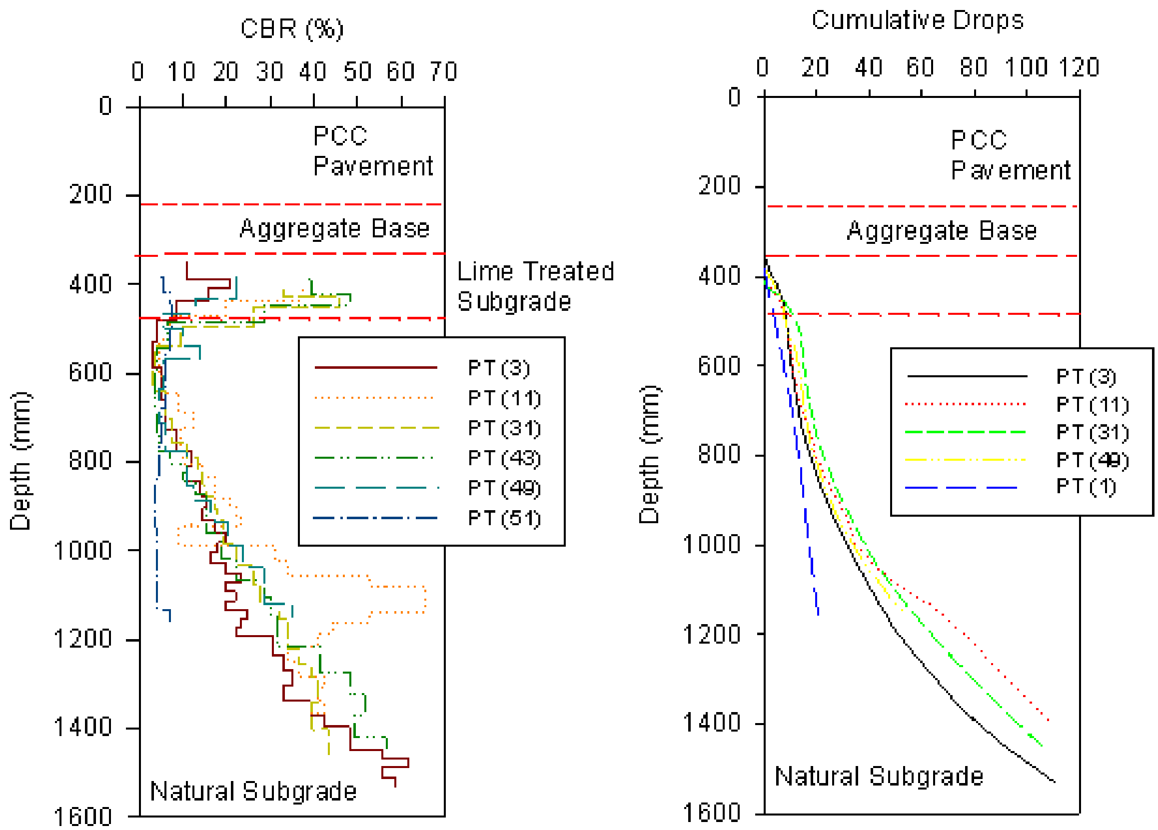


Figure 126. CBR – DCP profile and cumulative drops versus CBR of test points

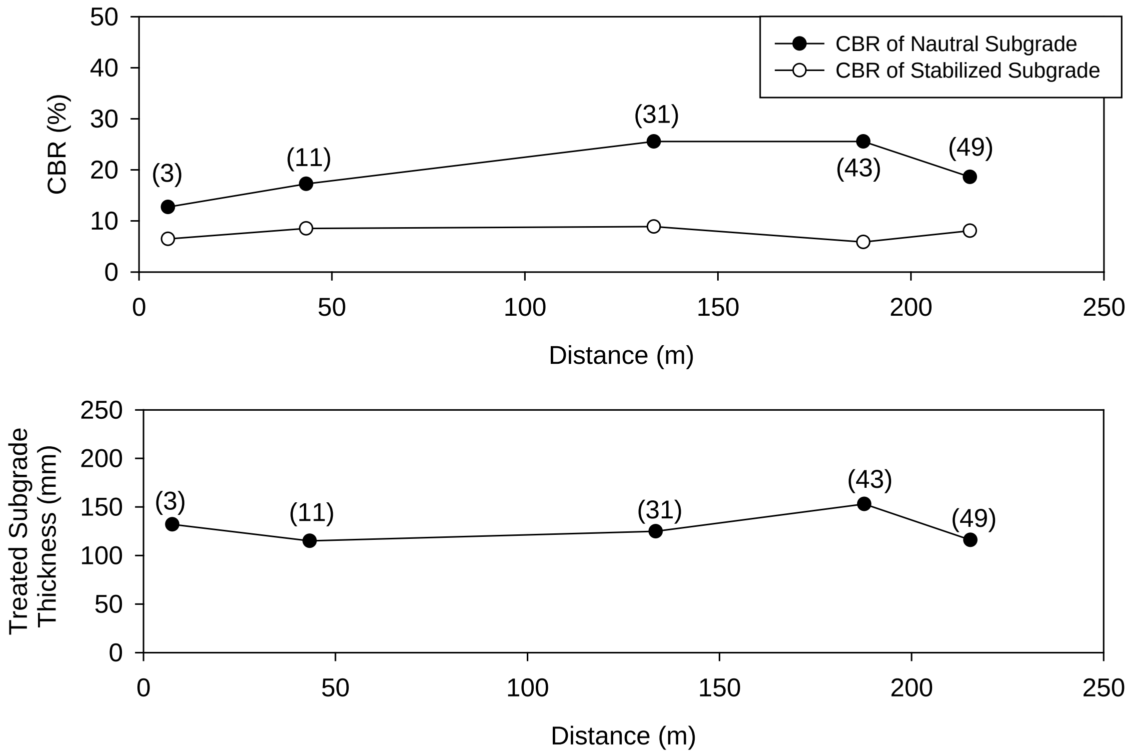


Figure 127. CBR and stabilized subgrade thickness from DCP profile

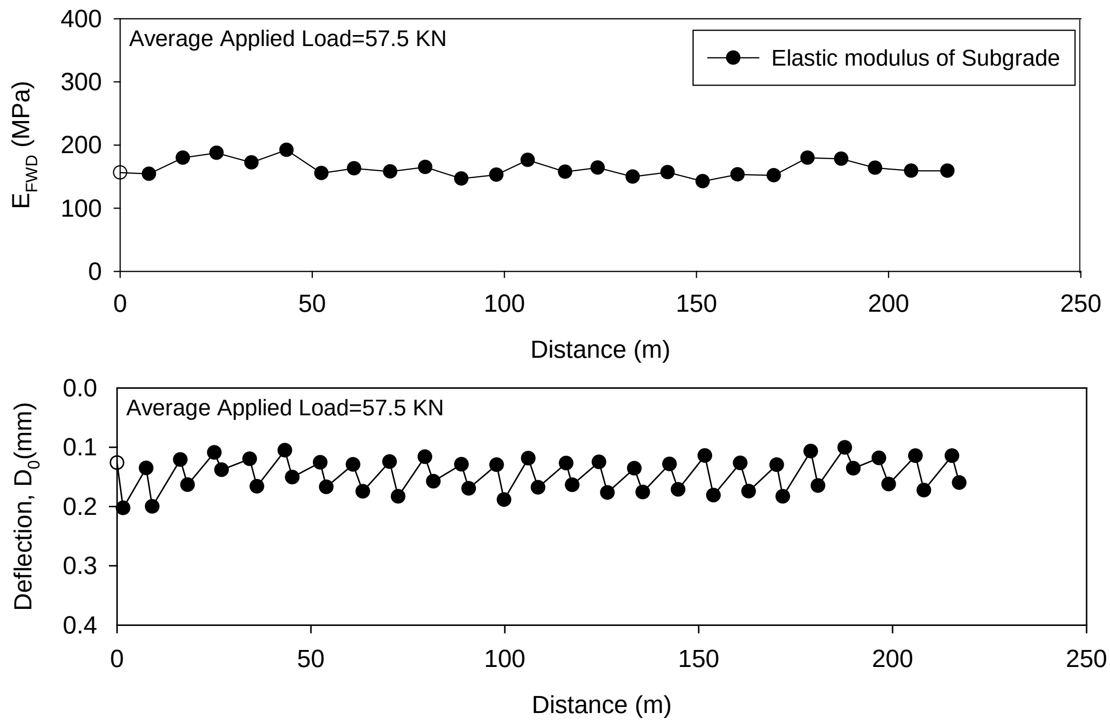


Figure 128.Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

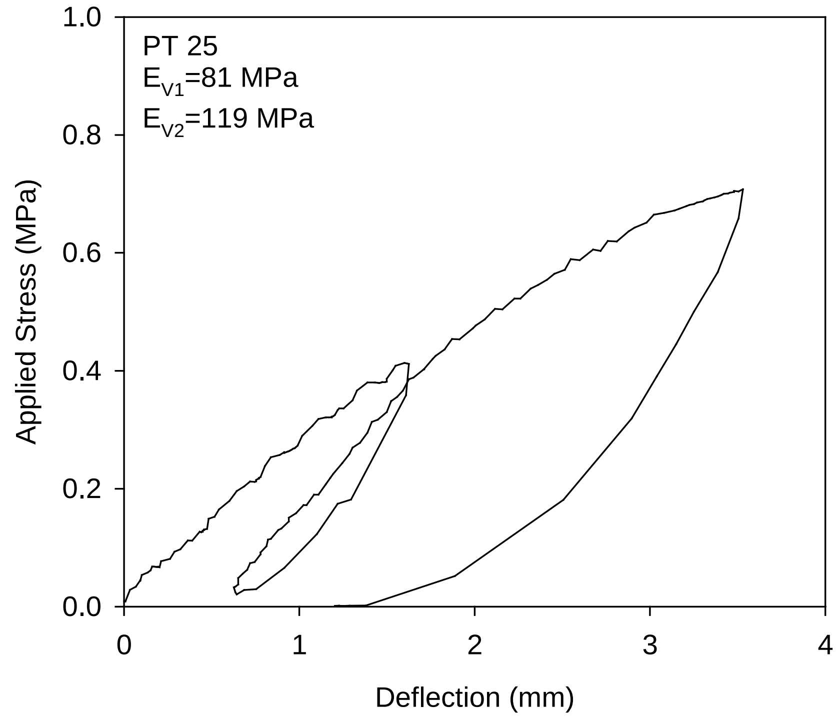


Figure 129. Stress – strain curves from plate load test at point 25

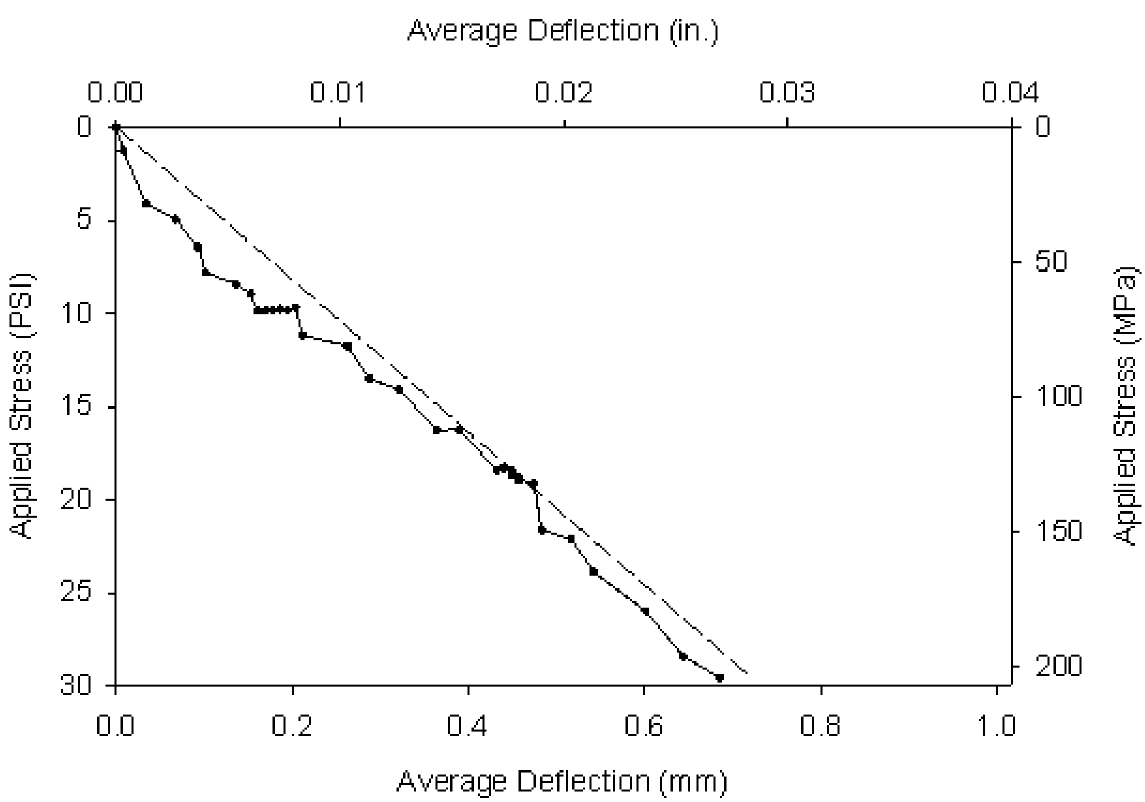


Figure 130. Stress – strain curves for obtaining KU at point 25

Table 38. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
25	Base	Top of base	81	81
25	Stabilized subgrade	Top of stabilized subgrade	91	91
51	Natural Subgrade	Top of natural subgrade	15	15

Table 39. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio	
CBR	E_{LWD}
2.9	6.1

Table 40. Summary statistics of test results from in-situ testing

Statistic	Base	Stabilized Subgrade						Natural Subgrade		FWD Def.
Measurement	E_{LWD}	CBR	E_{LWD}	k_U	E_{V1}	E_{V2}	Thi.	CBR	E_{LWD}	D_0
	MPa	%	MPa	kPa/mm	MPa	MPa	mm	%	MPa	mm
Number of Measurement (n)	1	5	1	1	1	1	5	6	1	50
Mean Value (μ)	81	20	91	103	81	119	128	7	15	0.15
Standard Deviation (σ)	—	6	—	—	—	—	16	2	—	0.03
Coefficient of Variation COV (%)	—	30	—	—	—	—	13	29	—	20

K 7, KS

Site Description

This project was located on the north bound of K 7 near south of Doniphan, in Doniphan County, Kansas. The general location is shown in Figure 131. This road is a two-lane State Highway. The road was constructed in 2005. The length of this test section is approximately 515 m (1690 ft). The design pavement consists of a 229 mm (9 in.) thick asphalt concrete (AC) and 300 mm (12 in.) fly ash stabilized subgrade. No base layer was presented in between subgrade and ACC pavement. The subgrade was stabilized with 14-18% fly ash. ISU research team conducted in-situ testing near milepost 223 on November 4, 2010 with assistance and traffic control provided by Kansas DOT.

The plan view of in-situ test locations is shown in Figure 132. The research team preformed FWD tests on the surface of ACC pavement at intervals of about 10-20 m from test points 1 to 31. DCP were conducted at test points 1, 3, 16, 29, 32, and 33. After coring, LWD and PLT were performed on the top of stabilized subgrade at test point 11. Bag samples were collected at test point 32 for natural soil and at test point 11 for subgrade.

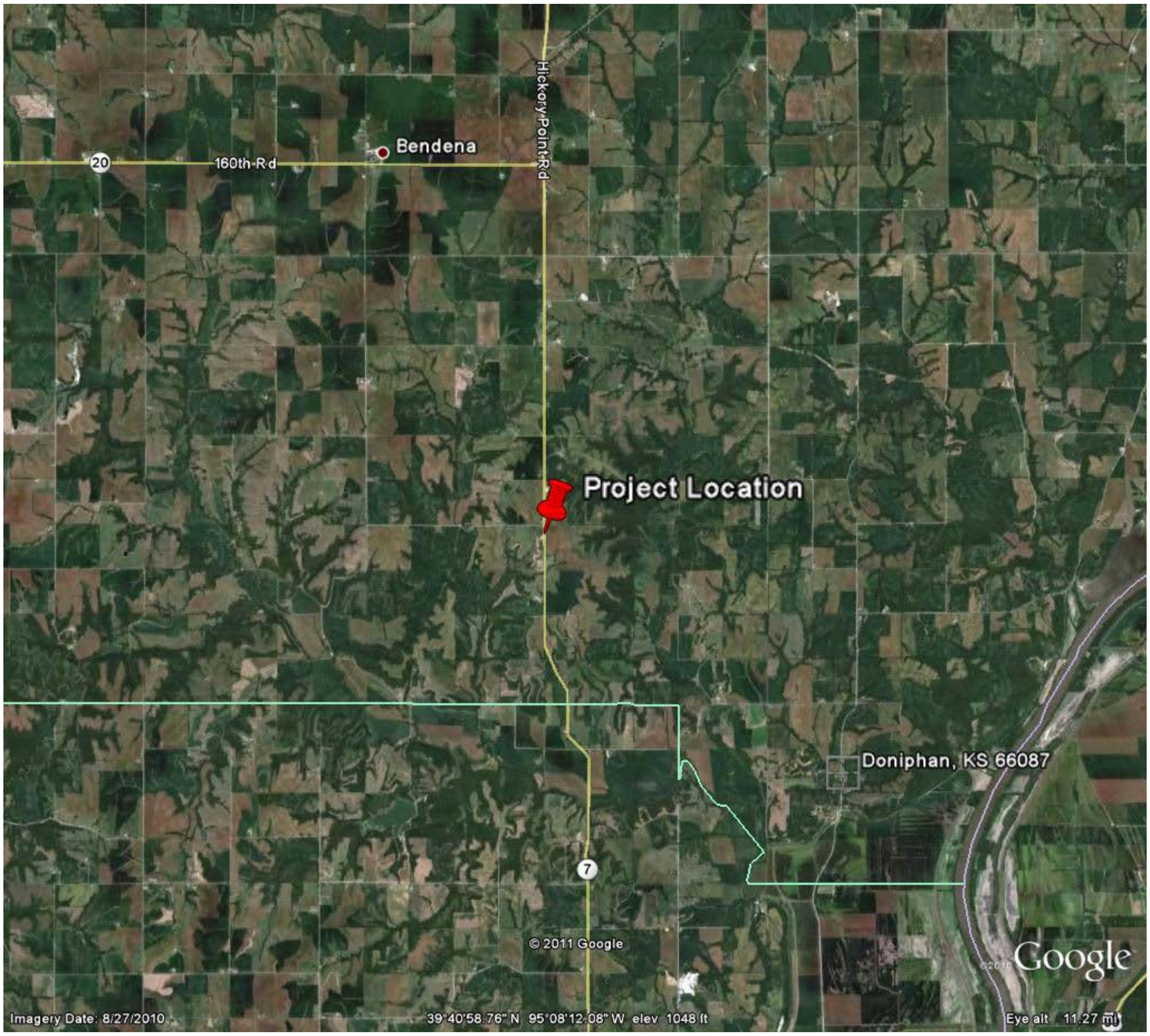


Figure 131. Project location of K 7 NB

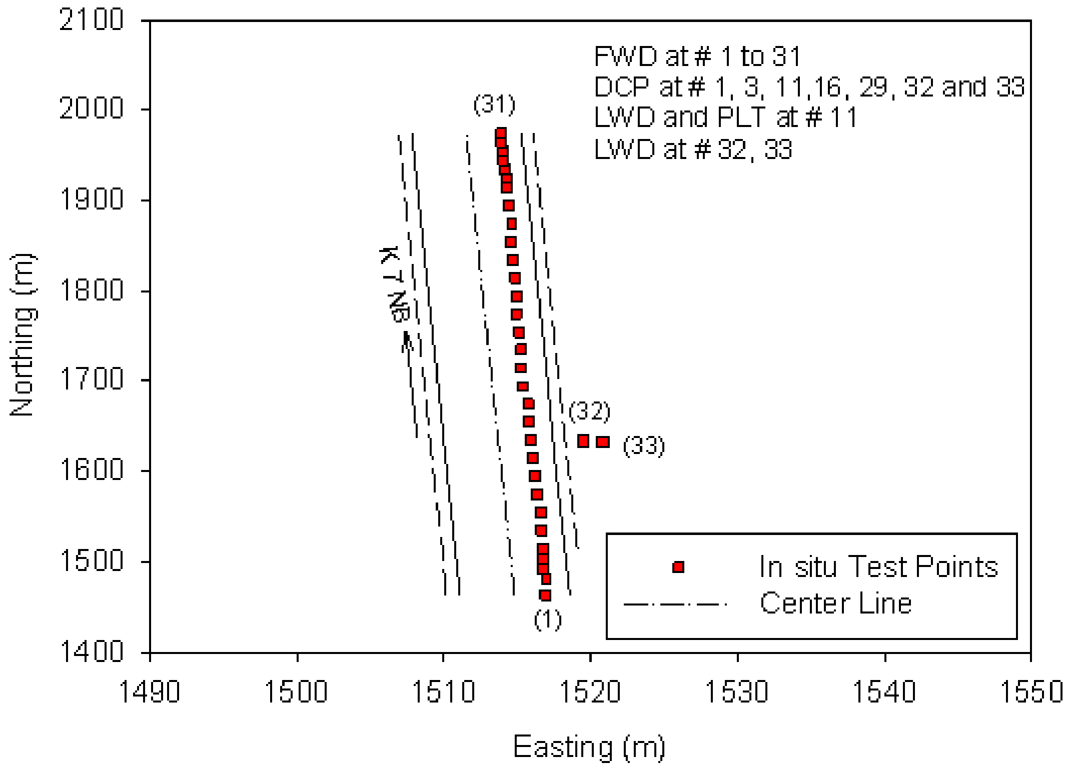


Figure 132. Test section plan layout

Figure 133. Site overview

Test Results and Analysis

Material Properties of Subgrade

The stabilized subgrade samples were taken at test point 11 from the top of subgrade to a depth of 300 mm (12 in.) at intervals of 50 mm (2 in.). The natural subgrade was collected at test point 32. According to USCS and AASHTO, the natural subgrade was classified as ML and A-4, and the stabilized subgrade was classified as SM and A-2-4, except A-1-b for stabilized subgrade from a depth of 51 mm to 102 mm. Table 41 provides material properties of subgrade. The average gravel content increased from about 1.1% for natural subgrade to 26.2% for stabilized subgrade, while the average sand content increased from about 4.6% to 41.7%. The average clay content decreased from about 20.2% for natural subgrade to 2.4% for stabilized subgrade, while the silt content decreased from about 74.1% to about 23.3%. The average LL value decreased from 38.4 for natural subgrade to 22.8 for stabilized subgrade, while the average PI value decreased from 18.3 to 5.1. Figure 134 shows particle size distribution curves of subgrade. Test results show the soil type of subgrade has been modified after treatment.

Table 41. Summary of material properties

Parameter	**K 7 KS**					
Material Description	Natural Sub.	Stab. Sub.	Stab. Sub.	Stab. Sub.	Stab. Sub.	Stab. Sub.
Depth mm (in.)	—	0-51 (0-2)	51-102 (2-4)	101-151 (4-6)	151-203 (6-8)	203-254 (8-10)
Gravel (%) (> 4.75mm)	1.1	26.2	37.4	34.0	23.1	25.8
Sand (%) (4.75mm–75µm)	4.6	46.6	39.8	38.8	49.6	46.0
Silt (%) (75µm–2µm)	74.1	25.2	19.9	24.8	24.9	26.0
Clay (%) (< 2µm)	20.2	2.0	2.9	2.4	2.4	2.2
C_u	—	421.1	574.7	541.6	361.0	425.5
C_c	—	1.3	3.6	1.0	1.3	2.0
Liquid Limit, LL (%)	38.4	23.0	23.2	22.1	22.3	22.1
Plasticity Index, PI	18.3	5.2	5.6	4.4	5.6	4.5
AASHTO	A-4	A-2-4	A-1-b	A-2-4	A-2-4	A-2-4
USCS	ML	SM	SM	SM	SM	SM
Water Content (%)	17.2	9.7	6.7	8.6	8.8	7.9

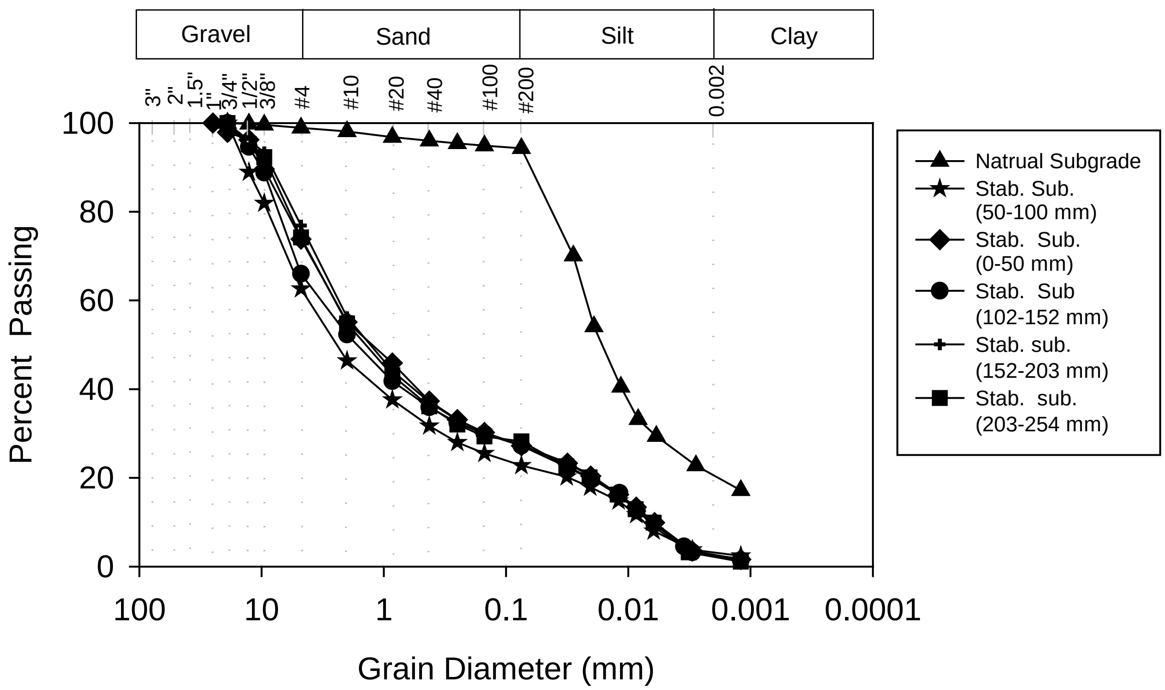


Figure 134. Particle size distribution curves for subgrade

pH of Stabilized and Natural Subgrade

Figure 135 shows the pH profile of subgrade at test point 11. The pH profile of stabilized subgrade increased gradually from the top to a depth of 300 mm subgrade. The pH of stabilized subgrade ranged from 7.8 to 8.3. The natural subgrade from the bag sample has a pH value of 7.4.

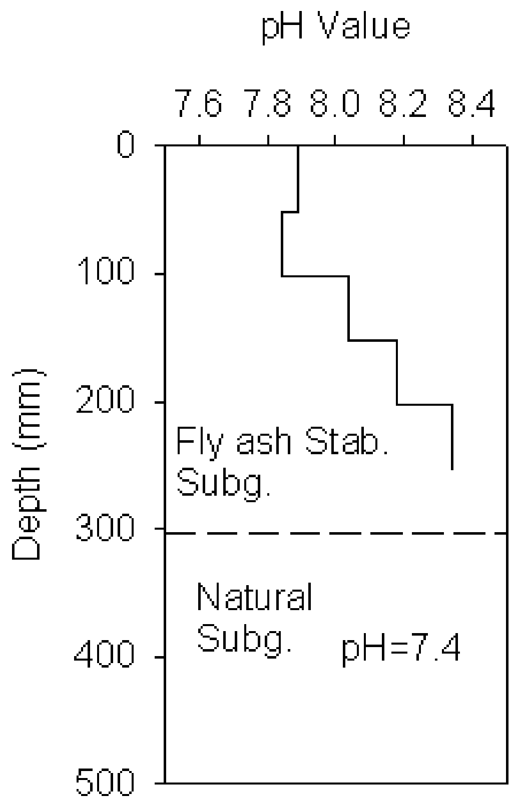


Figure 135. pH profile of subgrade

SEM Analysis

The energy dispersive spectrometry (EDS) map of natural subgrade is shown in Figure 136. The majority elements were silica (Si), alumina (Al), and oxygen (O). Additional present elements were potassium (K), iron (Fe), and calcium (Ca).

The energy dispersive spectrometry (EDS) map of stabilized subgrade is shown in Figure 137. The majority elements were Ca, Si, Al, and O. The mineral Ca has much higher concentration than Al, O, and Si. Additional present elements were Fe, K, and magnesium (Mg).

Figure 138 compares element concentration in Al, Si, O, S, Mg, Ca, K, and C for stabilized and natural subgrade. The stabilized subgrade sample shows higher concentration of Ca and C, less concentration of O, Al, and Si than the natural subgrade sample. All SEM images are presented in Figure 139, Figure 140, and Appendix D.

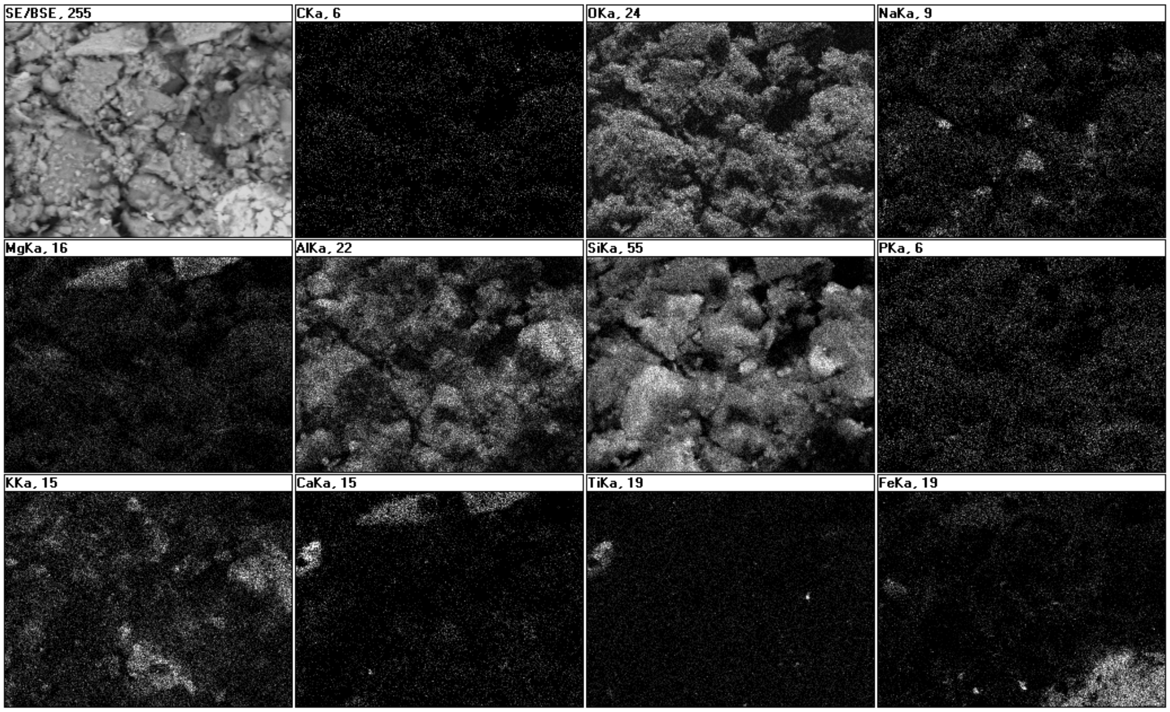


Figure 136. EDS map of natural subgrade sample (1000 ×)

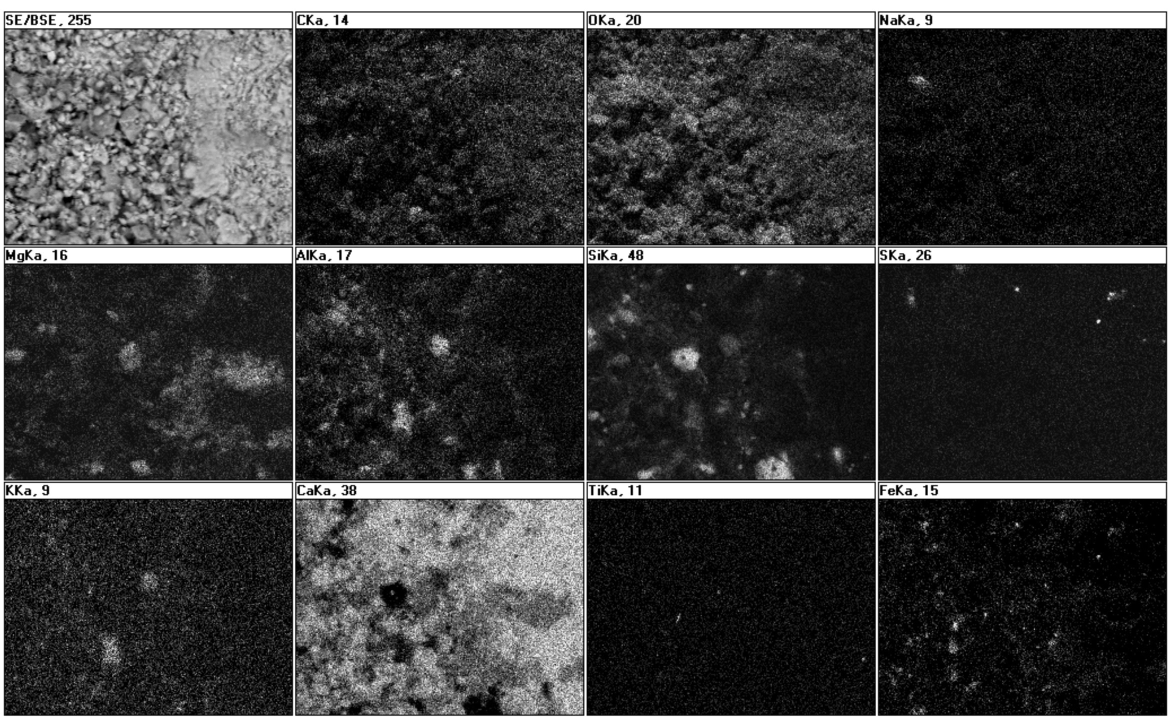


Figure 137. EDS map of stabilized subgrade sample (1000 ×)

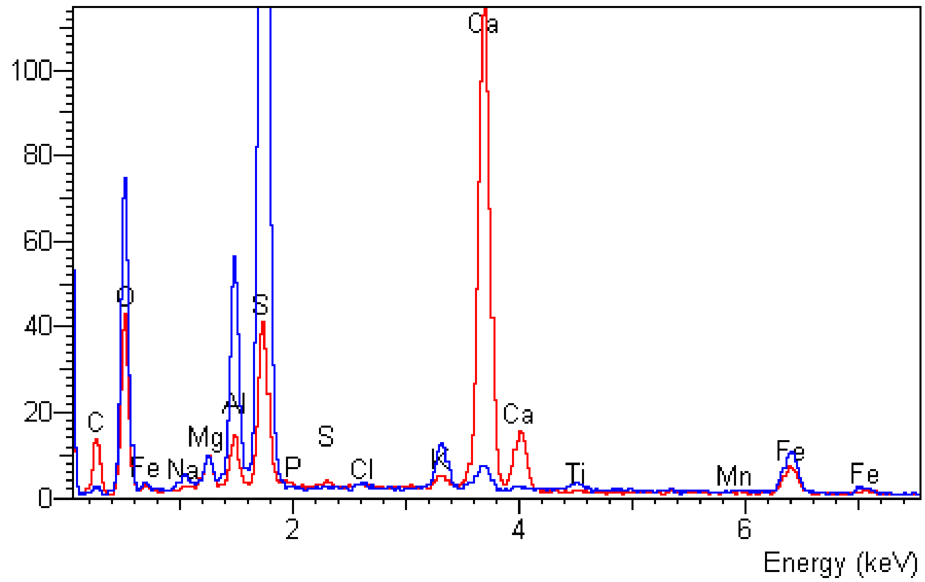


Figure 138. EDS intensity counts for stabilized subgrade sample (red line: 30×) and natural subgrade sample (blue line: 30×)

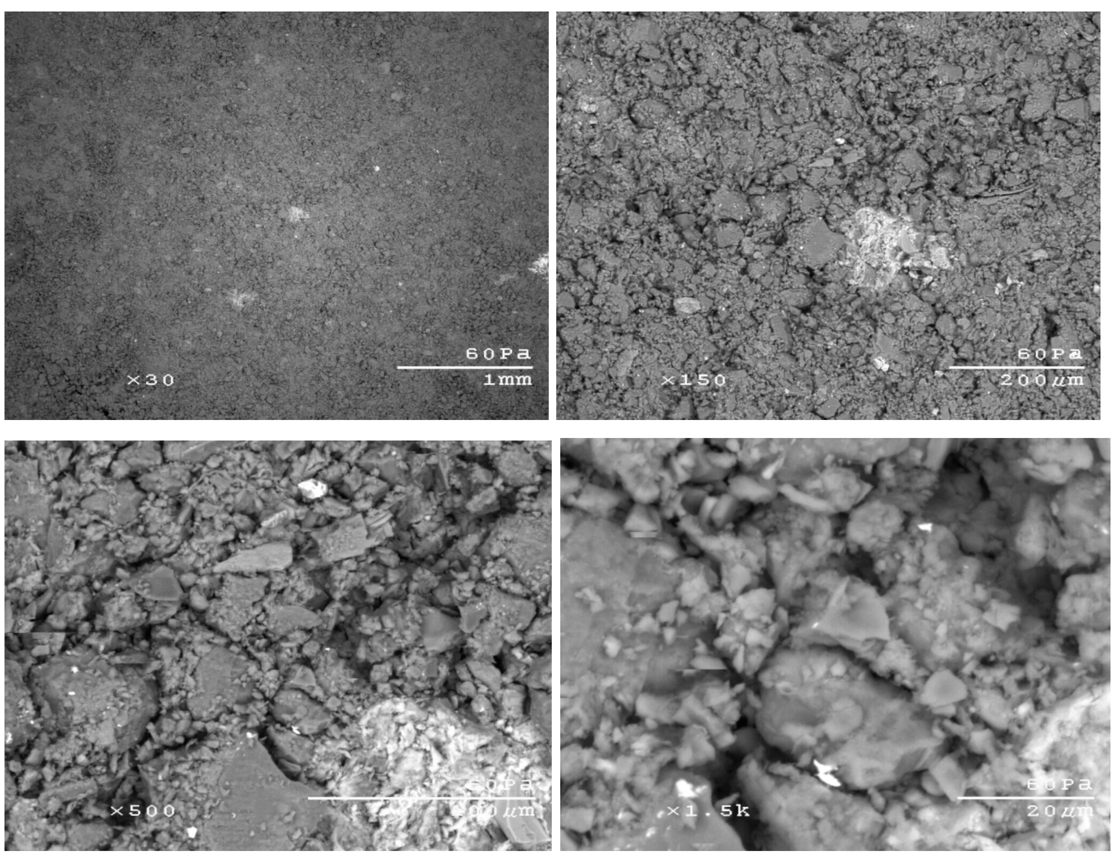


Figure 139. SEM images of natural subgrade

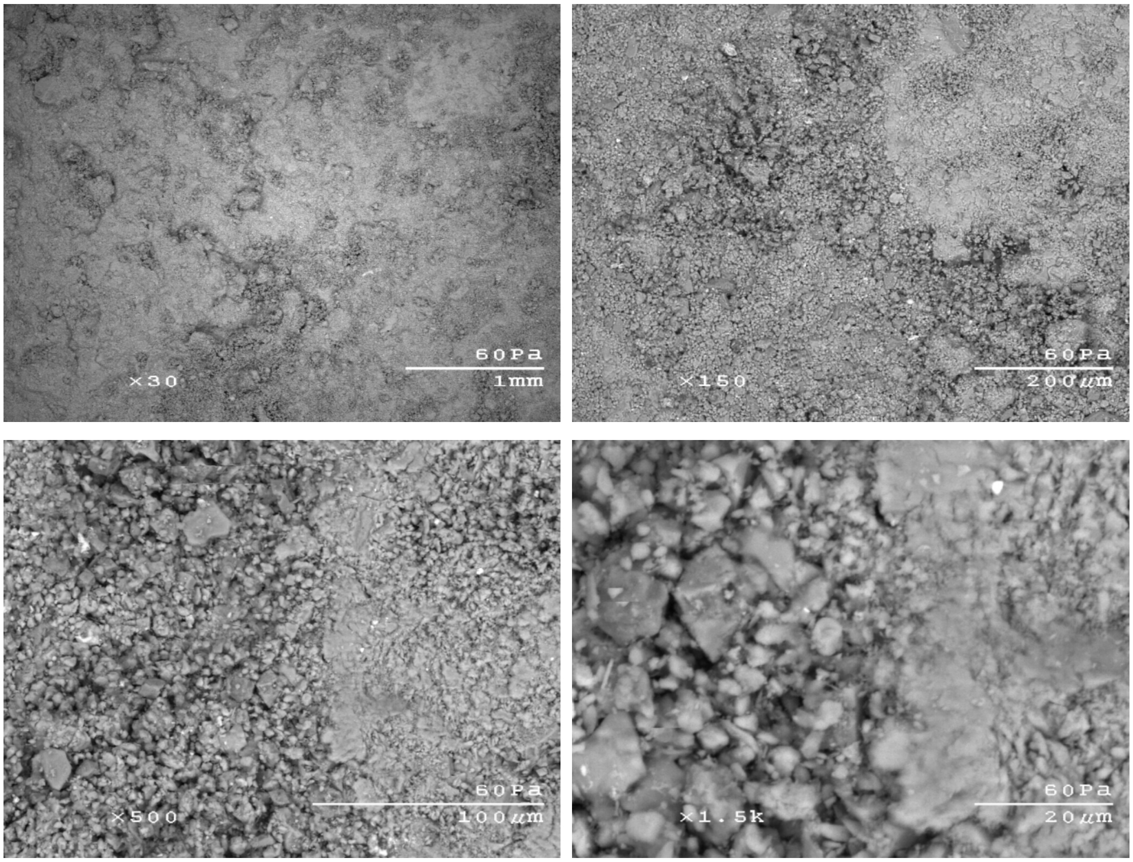


Figure 140. SEM images of stabilized subgrade

Stiffness and Strength

CBR values of stabilized and natural subgrade are converted from DPI using Equation (4). DCP profiles and cumulative drops versus CBR are shown in Figure 141. The average CBR of both natural and stabilized subgrade, and effective stabilized subgrade thickness are shown in Figure 142. The major observations are: (1) based on the effective treatment thickness, the average CBR of the stabilized subgrade was 72%, (2) the average CBR of the natural subgrade was 16%, (3) the average CBR of the stabilized subgrade was 450% of the natural subgrade, (4) the top and bottom layer of stabilized subgrade has a lower CBR than the middle layer, and (5) at test point 3, it is shown stiffness improvement was existed up to a depth of 800 mm (32 in.).

Backcalculated subgrade elastic moduli and deflections were presented in Figure 143. In the backcalculation, the applied test load was 57.5 KN (12928 lb). The assumptions of poison’s ratio were 0.35, 0.40, and 0.40 for ACC surface layer, stabilized subgrade and natural subgrade layer respectively. Stabilized subgrade moduli were calculated based on designed or effective stabilized subgrade thickness obtained from DCP profiles. Detailed assumptions of seed values and layer thickness are summarized in Appendix E. Deflections under the loading plate (D_0) were adjusted to a standard temperature of 20 ^{0}C (68 ^{0}F) using Equation (5). The temperature of middle depth of ACC pavement was measured as 9.8 ^{0}C (49.3 ^{0}F) prior to FWD testing. The key findings are:

- The average uncorrected deflection was about 0.22 mm, and corrected deflection was about 0.34 under average applied load. As deflection decreases, backcalculated E_{FWD} of both stabilized and natural subgrade increase.
- The average E_{FWD} was 138 MPa for natural subgrade and increased to 503 MPa for stabilized subgrade.
- The average E_{FWD} of stabilized subgrade was about 370% of natural subgrade
- The values of E_{FWD} of subgrade varied significantly indicating non-uniform subgrade soil properties.

Figure 144 presents the stress-strain relationships at test point 11. The value of E_{V1} and E_{V2} were calculated in the first circle and after reloading. The uncorrected modulus of soil reaction k′u was calculated using deflection under a load of 69.0 kPa as shown in Figure 145. The correction of k′u was made using the curve in Figure 8. The average E_{LWD} was increased 660% from 18 MPa for natural subgrade to 118 MPa for stabilized subgrade. The average E_{LWD} of stabilized subgrade was equal to 0.9 E_{V1} and 0.4 E_{V2}.

Table 42 lists all LWD test results. Table 43 provides the elastic modulus ratio between stabilized and natural subgrade. The mean value, standard deviation, and coefficient of variation of in-situ test results listed in Table 44. All in-situ results are presented in Appendix F.

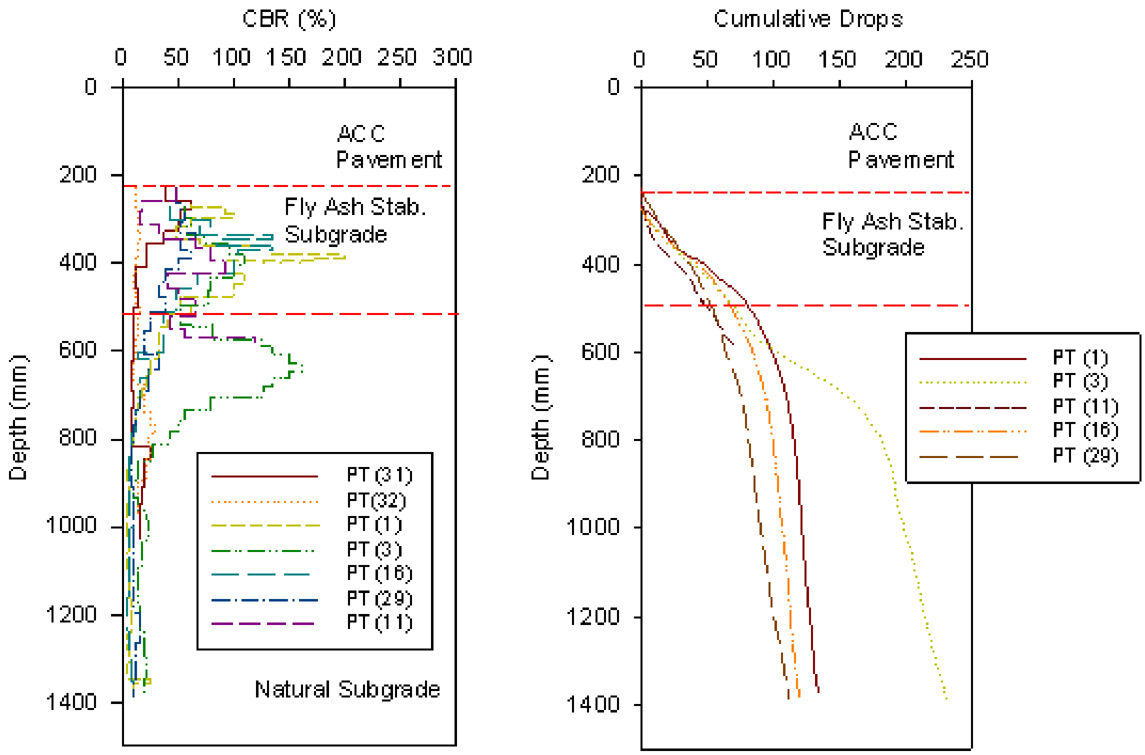


Figure 141. CBR – DCP profile and cumulative drops versus CBR of test points

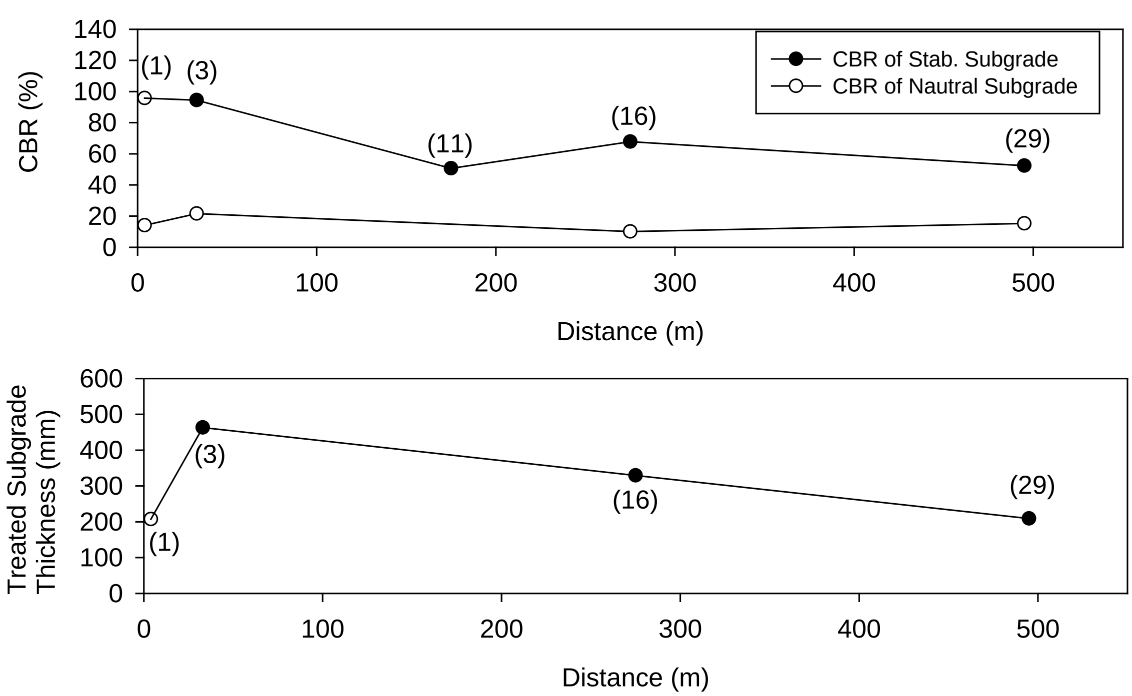


Figure 142. CBR and stabilized subgrade thickness from DCP profile

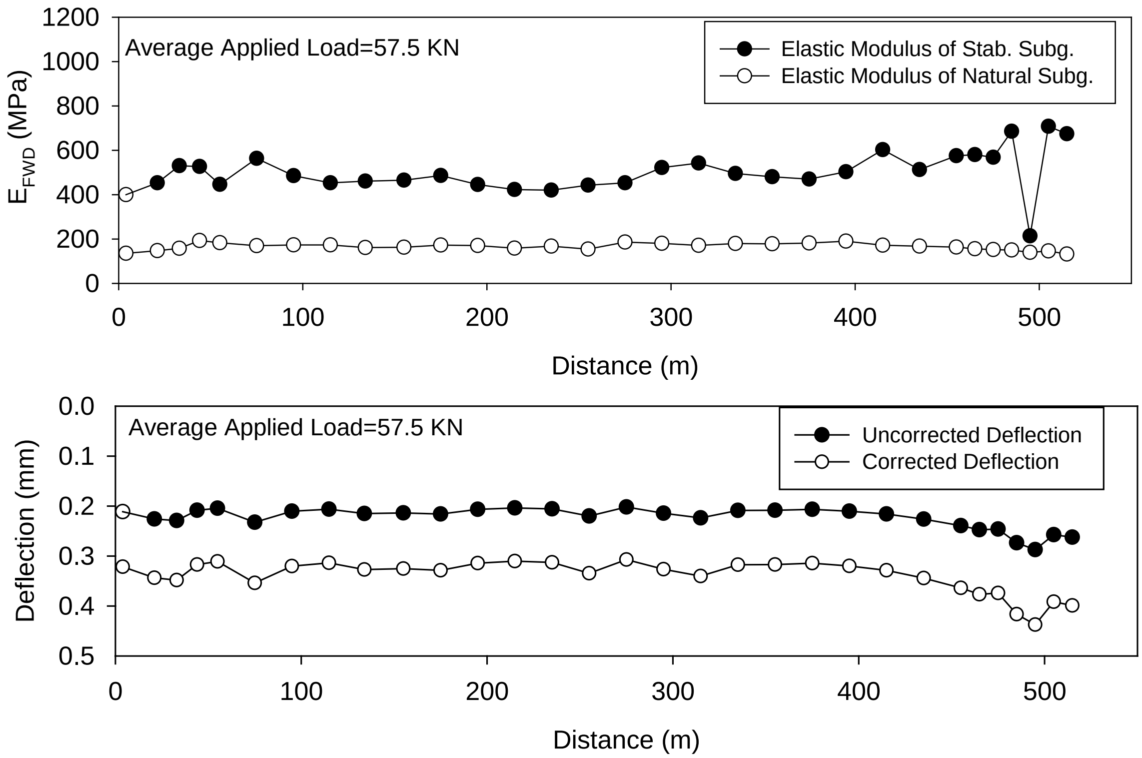


Figure 143. Backcalculated FWD elastic modulus of stabilized and natural subgrade, and deflections under the loading plate

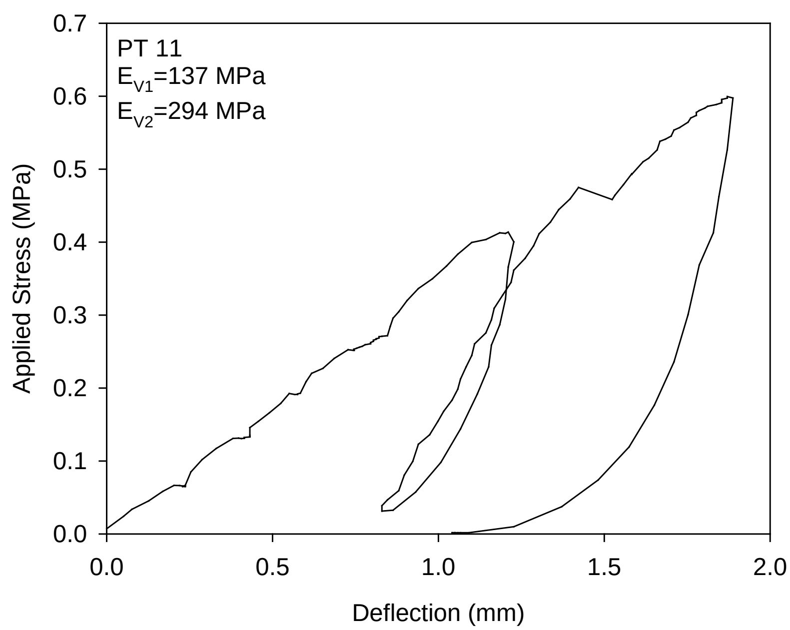


Figure 144. Stress – strain curves from plate load test at point 11

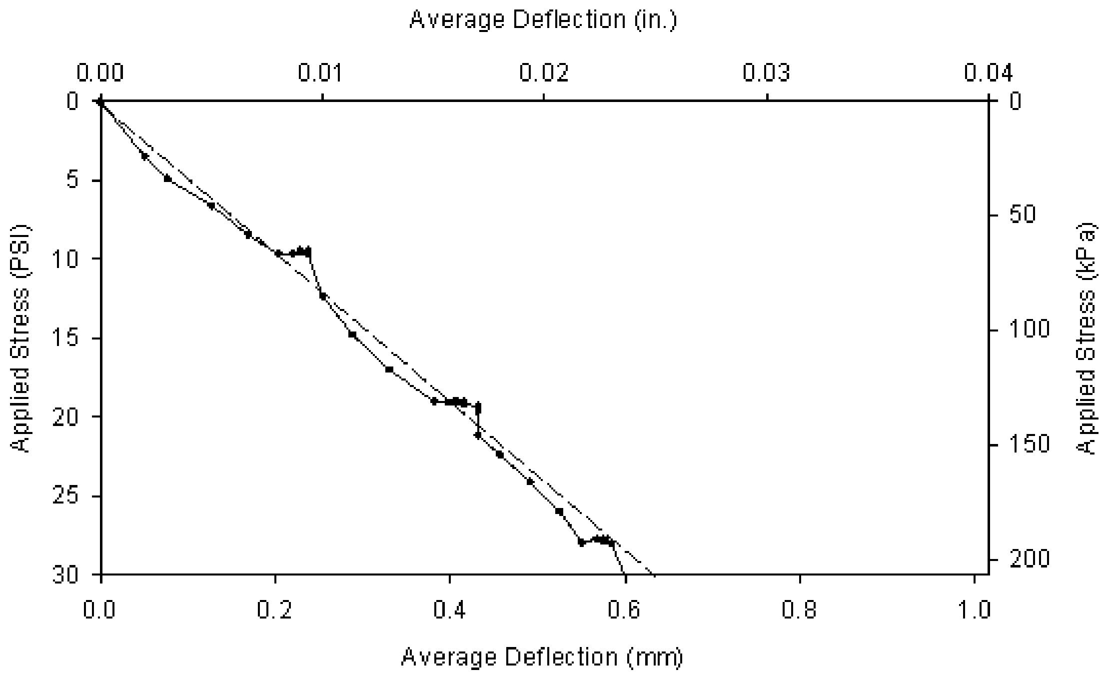


Figure 145. Stress – strain curves for obtaining K_U at point 11

Table 42. Summary of LWD test results

Test Point	Material Type	Depth of Measurement	E_{LWD}	Average E_{LWD}
			MPa	MPa
11	Stabilized Subgrade	Top of stabilized subgrade	89	89
32	Natural Subgrade	Top of natural subgrade	12	11
33	Natural Subgrade	Top of natural subgrade	10	

Table 43. Summary of elastic modulus ratio between stabilized and natural subgrade

Stab. Subg./Nat. Subg. Ratio		
CBR	E_{FWD}	E_{LWD}
5.3	3.7	10.8

Table 44. Summary statistics of test results from in-situ testing

Statistic	Stabilized Subgrade							Natural Subgrade			FWD Def
Meas.	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	k_U	Thi.	CBR	E_{FWD}	E_{LWD}	$D_{0\text{-Cor.}}$
	%	MPa	MPa	MPa	MPa	kPa/mm	mm	%	MPa	MPa	mm
Number of Meas. (n)	5	31	1	1	1	1	5	6	31	2	31
Mean Value (μ)	72	503	89	137	294	125	302	16	138	11	0.34
Standard Deviation (σ)	22	94	—	—	—	—	122	4	13	2	0.03
Coeff. of Variation COV (%)	30	19	—	—	—	—	40	27	10	13	10

SUMMARY

This chapter presented the test site information, laboratory, and in-situ test results. They are summarized and shown in Table 45. The background of test site includes site location, subgrade type, and ages of stabilized subgrade. Material properties of subgrade include soil type, fine contents, and plastic index. Based on in-situ testing results, design thickness and actual stabilization subgrade thickness were compared; average E_{V1}, E_{FWD}, E_{LWD}, CBR of subgrade are listed; modulus ratios are determined between stabilized and natural subgrade.

Table 45. Summary of laboratory and in-situ test results for all test sites

Test Site	Age (Yrs)	Subg. Type	Fines Cont. (%)	Soil Type	Plastic Index (%)	Ave. Thick (mm)	Design Thick (mm)	E_{VI} (MPa)	E_{LWD} (MPa)	E_{FWD} (MPa)	E_{CBR} (MPa)	Ratio Between Sta. and Nat. Subg.		
												CBR	E_{FWD}	E_{LWD}
SH 121	15	Stab. Sub	27.4	SM	N.P.	—	200	211	69	1129	119	—	4.3	—
FM 1709	16	Stab. Sub	40.6	SM	N.P.	—	150	129	180	396	53	2.2	3.1	—
US 287	28	Stab. Sub	44.4	ML/SM	15.4	—	356	150	65	926	163	7.4	8.3	—
US 183	11	Nat. Sub.	84.3	ML	10.2	176	203	—	19	144	29	4.5	12.3	8.5
		Sta. Sub.	35.0	SM	6.3			317	164	1794	133			
SH 99	11	Nat. Sub.	37.7	SM	4.9	220	203	—	16	238	27	3.8	1.6	4.1
		Sta. Sub.	44.7	SM	N.P.			63	65	369	103			
US 59	10	Nat. Sub.	65.9	ML	24.7	150	203	—	20	383	23	6.4	2.3	5.3
		Sta. Sub.	35.7	SM	5.6			177	105	819	139			
US 75 SB	15	Nat. Sub.	96.7	ML	33.1	111	100	—	—	323	11	2.7	2.2	—
		Sta. Sub.	44.5	ML/SM	21.1			7	31	711	30			
US 75 NB	15	Nat. Sub.	68.9	ML	34.3	128	152	—	15	—	7	2.9	—	6.1
		Sta. Sub.	34.6	SM	7.8			81	91	—	20			
K 7	5	Nat. Sub.	94.3	ML	18.3	302	300	—	11	138	16	5.3	3.7	10.8
		Sta. Sub.	26.6	SM	5.1			137	89	503	72			

CHAPTER 5 SUMMARY AND CONCLUSIONS

Nine test sites were selected to access the long-term performance of lime or fly ash stabilized subgrades. Ages of these stabilized subgrades ranged from 5 to 28 years. In-situ tests were conducted on eight ACC pavements and one PCC pavement. FWD moduli were backcalculated using the ERI data analysis program. Test results from the nine site studies led the following conclusions are made:

- Fine contents of subgrades were reduced by 30-68% after treatment. At the majority of test sites, the types of natural subgrades were modified from ML to SM after treatment. Stabilized subgrades at three sites were non-plastic soils. PI values of natural subgrades were reduced by 4-24% after treatment.
- Four elements, Ca, Al, Si, and O commonly present in stabilized subgrades. Based on SEM analysis of natural and stabilized subgrade at the US 183 site, the new cementing compounds formed and existed in stabilized subgrade. Those cementing compounds resulted from pozzolanic reactions that increase soil strength.
- The average elastic modulus ratio determined from LWD for stabilized subgrade varied from 31 to 180 MPa, and the average elastic modulus ratio for natural subgrade varied from 11 to 20 MPa. LWD modulus ratios between stabilized and natural subgrade ranged from 4.1 to 10.8.
- CBR ratios between stabilized and natural subgrade ranged from 2.2 to 7.4. CBR ranges from 20 to 163. The LWD and FWD modulus are 0.7 to 8.3 times the PLT modulus. The value of elastic modulus is dependent on varied testing methods.
- The effective stabilized thickness was 26% varied from the designed stabilized subgrade thickness.
- The average PLT elastic modulus has a range from 7 to 317 MPa for nine test sites. The MEPDG recommended that the typical elastic modulus of lime stabilized soil ranges from 240 to 413 MPa. Most of test sites had modulus out of this range. Additionally, a deteriorated modulus for lime stabilized soil is less than 103 MPa. Two lime stabilized subgrades showed modulus values are less than 103 MPa.

CHAPTER 6 RECOMMENDATIONS

The following recommendations should guide future research to establish good case studies of long-term performance of chemical stabilized subgrades.

- Conduct life cycle cost analysis for using stabilized subgrade in structural pavement design
- Backcalculate the subbase layer coefficient to determine the structural benefit provided by those stabilized subgrades. In the backcalculation, treat the stabilized subgrade as the subbase layer.
- Conduct resilient modulus tests on undisturbed stabilized subgrade samples and compare these resilient modulus values with backcalculated FWD modulus values.
- Conduct x-ray diffraction (XRD) and x-ray fluorescence (XRF) tests to quantitatively analyze chemical reaction byproducts in stabilized subgrades.
- Compare other stabilization technologies (e.g., mechanical stabilization using geosynthetics, fiber reinforcement) with chemical stabilization of subgrade
- Document the long-term performance of stabilized subgrade with cement or combined stabilizers

In the field, it is important to follow QC/QA programs that improves construction quality to uniformly mix and compact chemical stabilized subgrade.

REFERENCES

AASHTO. (1993). Guide for Design of Pavement Structures. AASHTO, Washington, D.C.

AASHTO. (2002). Guide for Design of Pavement Structures. AASHTO, Washington, D.C.

AASHTO. (2008). "Standard method of test for nonrepetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements." American Association of State Highway and Transportation Officials, Washington, D.C.

Officials, Washington, D.C.

Adaska, W. S., and Luhr, D. R. (2004). "Control of Reflective Cracking in Cement Stabilized Pavements." *The 5th International RILEM Conference, Cracking in Pavements – Mitigation, Risk Assessment and Prevention*, Limoges, France,

American Association of State Highway and Transportation Officials (AASHTO) (2008). "Section 307. Lime-Treated Courses," *Guide Specifications for Highway Construction*, Washington, D.C.

ACAA. (2008). *Soil stabilization and pavement recycling with self-cementing coal fly ash.* American Coal Ash Association, Aurora, CO. 1-70.

Addison, M. B., and Polma, F. A. (2007). "Extending durability of lime modified clay subgrades with cement stabilization." *GeoDenver 2007, GSP-172: Soil Improvement,* February, Denver, Colorado, 1-10.

Aiban, S. A., Al-Abdul Wahhab, H. I., Al-Amoudi, O. S. B., and Ahmed, H. R. (1998). "Performance of a stabilized marl base: a case study." *Construction and Building Materials*, 12(6–7), 329–340.

Air Force Joint Pamphlet (1994). Planning and Design of Roads, Airfields, and Heliports in the Theater of Operations—Road Design. Field Manual No. 5-430-00-1, Washington, DC. <*http://www.globalsecurity.org/military/library/policy/army/fm/5-430-00-1/CH5.htm*> (August 15, 2009)

Alabama Department of Transportation (2008). “Section 231-Stabilized Roadbed, Section 232-Lime Stabilized Roadbed,” *Standard Specifications for Highway Construction*, Montgomery, Alabama.

Alberta Infrastructure and Transportation (2007). “Section 3.5-Asphalt Stabilized Base Course, Section 3.9-Cement Stabilized Base Course,” Standard Specifications for Highway Construction, Edmonton, Alberta.

Arkansas Department of Transportation (2003). “Section 301- Lime Treated Subgrade, Section 308-Cement Stabilized Crushed Stone Base Course,” Arkansas 2003 Standard Specification for Highway Construction.

Army and Air Force (1994). *Soil Stabilization for Pavements*. Joint Departments of the Army, the Navy and Air Force, Washington, DC.

ASTM. (1993). “Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements.” *Annual book of ASTM Standards, ASTM D1195*, West Conshohocken, PA.

ASTM. (1993). “Standard test method for nonrepetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements.” *Annual book of ASTM Standards, ASTM D1196*, West Conshohocken, PA.

ASTM. (2000). “Standard classification of soils for engineering purposes (Unified Soil Classification System).” *Annual book of ASTM Standards, ASTM D2487*, West Conshohocken, PA.

ASTM. (2003). “Standard test method for use of the dynamic cone penetrometer in shallow pavement applications.” *Annual Book of ASTM Standards, ASTM D6951*, West Conshohocken, PA.

ASTM. (2003). “Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils.” *Annual Book of ASTM Standards, ASTM D2850*, West Conshohocken, PA.

ASTM. (2005). “Test methods for liquid limit, plastic limit, and plasticity index of soils.” *Annual Book of ASTM Standards, ASTM D4318*, West Conshohocken, PA.

ASTM. (2009). “Standard Test Method for Particle-Size Analysis of Soils.” *Annual Book of ASTM Standards, ASTM D422-63,* West Conshohocken, PA.

ASTM. (2009). “Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.” *Annual Book of ASTM Standards, ASTM D 2216,* West Conshohocken, PA.

ASTM. (2007). “Standard Test Method for pH of Soils.” *Annual Book of ASTM Standards, ASTM D 4972-01*, West Conshohocken, PA.

Austroads (1998). *Guide to Stabilisation in Roadworks*. National Association of Australian State Road Authorities, Australia.

Bhatty, J. I., Bhattacharja, S., and Todres, H.A. (1996). “Use of cement klin dust stablizating clay soils.” Portland Cement Association. Skokie, Illinois. 1-27.

Brazetti, R., and Murphy, S.R. (2001). “Performance Results of Soil Stabilization Programs in Latin America.” *Proceedings of Second International Symposium on Maintenance and Rehabilitation of Pavement and Technological Control*, Auburn, Alabama, 1-13.

Buhler, R. L., and Cerato, A. B. (2007). “Stabilization of Oklahoma Expansive Soils Using lime and Class C Fly ash.” GeoDenver 2007, GSP-162: Problematic Soils and Rocks and In-situ Characterization, February, Denver, Colorado, 1-10.

Burnham, T., and Johson, D. (1993). In-situ foundation characterization using the dynamic cone penetrometer. Final Report, Minnesota Department Transportation, Office of Research Administration, St. Paul, MN.

California Department of Transportation (2006). “Section 24- Lime Stabilization, Section 27: Cement Treated Bases,” *Standard Specifications,* Sacramento, California.

Chen, J. Z., Hossain, M., and LaTorella, T. M. (1999). “Use of Falling Weight Deflectometer and Dynamic Cone Penetromter in Pavement Evaluation.”*Journal of the Transportation research Borad.*1655, Washington D.C.

Christopher, B. R., Schwartz, C., and Boudreau, R. (2006). *Geotechnical Aspects of Pavements.* Rep. No. FHWA-NHI-05-037, U.S. Department of Transportation, Federal Highway Administration, Washington D.C.

City of College Station (2009). "SECTION 32 11 34-Cement Stabilization of Material in Place, Section 32 11 29-Lime Stabilization." City 0f Tucson and Pima County *Standard Specifications for Public Improvements.*

Colorado Department of Transportation (2005). "Section 307-Lime Treated Subgrade," Standard Specifications for Road and Bridge Construction.

Crovetti, J. A., Shahin, M. Y., and Touma, B. E. (1989). "Comparison of two falling weight deflectometer devices, Dynatest 8000 and KUAB 2M-FWD." SPT 1026. Nondestructive Testing of Pavements and Backcalculation of Moduli.

Daniels, J. L., and Janardhanam, R. (2007). "Cold weather subgrade stabilization." *GeoDenver 2007, GSP-172: Soil Improvement*, February, Denver, Colorado, 1-10.

Delaware Department of Transportation (2001). "Section 304-Asphalt Stabilized Base Course," *Specifications for Road and Bridge Construction.*

Department of the Army (1992). *Military Soil Engineering.* Field Manual 5-410, Washington D.C., 9-1-9-81.

Eades, J. L., and Grim, R. E. (1966). A quick test to determine lime requirements for lime stabilization, *Highway Research Record 139*. HRB. National Research Council, Washington, D.C.

EPRI. (1992). *Fly Ash Design Manual for Road and Site Applications.* Volume 1: Dry or Conditioned Placement, Electric Power Research Institute, EPRI-TR-100472, Research Project 2422-2, Final Report, prepared by GAI Consultants, Inc., Monroeville, Penn., April. 6-1-6-39

ERI. (2009). *ERI Data Analysis User's Guide.* Engineering and Research International, Inc. Savoy, Illinois.

Ese, D., Myre, J., Noss, P., and Vaerness, E. (1994). "The Use of the Dynamic Cone Penetrometer (DCP) for Road Strengthening Designs in Norway." Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields, University of Minnesota, Minneapolis, MN.

Federal Highway Administration (FHWA) (2003). "Section 305-Treated Aggregate Courses," *Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects.* U.S. Department of Transportation, Washington, D.C.

Fleming, P. R. (2001). "Field measurement of stiffness modulus for pavement foundation." Transportation Research Board, Paper No. 01-2145.

Fwa, T. F. (2006). *The handbook of highway engineering*, Edit by T.F. Fwa. Taylor & Francis Group. Boca Raton, FL. P.20-1

Florida Department of Transportation (2010). "Section 287-Asphalt Treated Permeable Base, Section 288-Cement Treated Permeable Base," *Standard Specifications for Road and Bridge Construction*.

Georgia Department of Transportation (2001). "Section 225-Soil-Lime Construction, Section 301-Soil-Cement Construction, Section 302-Sand-Bituminous Stabilized Base Course," *Standard Specifications Construction of Transportation Systems*, Atlanta, Georgia.

Glogowski, P. E., Kelly, J. M., McLaren, R. J., and Burns, D. L. (1992). *Fly Ash Design manual for Road and Site Application.* Volume 1: Dry or Conditioned Placement.

Gourley, C. S., and Greening, P. A. K. (1999). *Performance of Chemically Stabilised Roadbases: Results and Recommendations from Studies in Southern Africa*. Project Report No. R6020, Transport Research Laboratory.

Harison, J. A. (1989). "Correlation between California Bearing Ratio and Dynamic Cone Penetrometer Strength Measurements of Soils." Australian Road Research, 19(4).

Hong, G. T., Aubeny, C. P., Bulut, R., and Lytton, R. L. (2006). "Design of pavements on expansive soils." *GSP-147: Unsaturated Soils 2006*, 427-438.

Hopkins, T. C., Hunsucker, D., and Sharpe, G. W. (1988). "Highway Field Trials of Chemically Stabilized Soil Subgrades." *Proceedings of Ohio River Valley Soils Seminar XIX*, October, Lexington, Kentucky.

Hopkins, T. C., Beckham, T. L. and Hunsucker, D. Q. (1995). *Modification of Highway Soil Subgrades.* Rep. No. KTC 94-11, Kentucky Transportation Center, College of Engineering, University of Kentucky.

Hopkins, T. C., and Beckham, T. L. (1999). "Long-Term Performance of a Highway Subgrade Stabilized with an Atmospheric Fluidized Bed Combustion Material." *1999 International Ash Utilization Symposium*, Center of Applied Energy Research, University of Kentucky, Kentucky, 1-12.

Hopkins, T. C., Beckham, T. L, Sun, L., Ni, B., and Butcher, B. (2002). *Long-Term Benefits of Stabilizing Soil Subgrades.* Rep. No. KTC-02-09/SPR-196-99-1F, Kentucky Transportation Center, College of Engineering, University of Kentucky.

Hossain, M. S., and Apeagyei, A. K. (2010). Evaluation of the Lightweight Deflectometer for In-situ Determination of Pavement Layer Moduli. Virginia Transportation Research Council. Charlottesville, VA. http:/www.virginiadot.org/vtrc/main/online_reports/pdf/10-r6.pdf. Accessed July 18, 2011.

Huat, B. B. K., Alias, A., and Aziz, A. A. (2008). "Evaluation, Selection and Assessment of Guidelines for Chemical Stabilization of Tropical Residual Soils." *American Journal of Environmental Sciences*, 4(4), 303-309.

Illinois Department of Transportation (2005). Subgrade Stability Manual. Bureau of Bridges and Structures. Springfield, IL

Illinois Department of Transportation (2007). "Section 302-Soil Modification, Section 312-Stabilized Subbase, Section 350-Lime Stabilized Soil Mixture," *Standard Specifications for Road and Bridge Construction.*

Jung, C., and Bobet, A. (2008). Post-Construction Evaluation of Lime-Treated Soils. Report Number:FHWA/IN/JTRP-2007/25. Joint Transportation Research Program. Indiana Department of Transportation, West Lafayette, IN

Kansas Department of Transportation (2007). “Section 301-Subgrade Modification,” *Standard Specifications for State Road and Bridge Construction,* Topeka, Kansas.

Kim, Y. R., Hibbs, B. B., and Lee Y. C. (1995). *Temperature Correction of Deflection and Backcalculated Asphalt Concrete Moduli,* Transportation Research Board 1473, TBR, National Research Council Washington, D.C., pp. 55-62

Kleyn, E.G. (1975). *The Use of the Dynamic Cone Penetrometer (DCP).* Transvaal Roads Department, Report L2/74, Pretoria, South Africa.

Kota, P. B. V. S, Hazlett, D., and Perrin, L. (1996). “Sulfate-Bearing Soils: Problems with Calcium-Based Stabilizers.” *Transportation Research Board*, 1757, 62-69.

Laguros, J. G., and Miller, G. D. (1997). “Stabilization of Existing Subgrades to Improve Constructability During Interstate Pavement Reconstruction.” *National Cooperative Highway Research Program (NCHRP) Synthesis 247*, Transportation Research Board, Washington, D.C., 1-36.

Lee, C., Lee J.-S., Lee, W., Yoon, H.-K., Cho, T.-H., and Quang, T. H. (2007). “Cementation effects on rigid-soft particle mixtures.” *GeoDenver 2007, GSP-172: Soil Improvement*, February, Denver, Colorado, 1-10.

Little, D. N., Scullion, T., Kota, P. B. V. S., and Bhuiyan ,J. (1995 a). *Identification of the structural benefits of base and subgrade stabilization*. Texas Transportation Institute, Texas A&M University Systeml, College Station, Texas.

Little, D. L., Scullion, T., Kota, P. B. V. S., and Bhuiyan, J. (1995 b). *Guidelines for Mixture Design and Thickness Design for Stabilized Bases and Subgrades.* Rep. No. FWHA/TX-951287-3F, Texas Transportation Institute, Texas.

Little, D. N. (1995). Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime. Kendall / Hunt Publishing Company, Dubuque, Iowa.

Little, D. L. (1996). “Assessment of In-situ Structural Properties of Lime-Stabilized Clay Subgrades.” *Transportation Research Record*, 1546, 13-23.

Livneh, M. (2007). “Uncertainty associated with pre-defined correlative expressions of various in-situ test outputs.” *The 2007 FAA Worldwide Airport Technology Transfer Conference,* Atlantic City, New Jersey, USA

Livneh, M., and Goldberg, Y. (2001). “Quality Assessment During Road Formation and Foundation construction, Using of Falling-Weight Deflectometer and Light Weight Drop Weight.” Transportation Research Record 1755, p 69-77.

Louisiana Department of Transportation (2006). “Section 304-Lime Treatment, Section 303-In-Place Cement Stabilized Base Course, Section 308-In-Place Cement Treated-Base Course.” *Standard Specifications for Roads and Bridges.*

Minnesota Department of Transportation (2009). “LWD Deflection method” http://www.dot.state.mn.us/materials/gradingandbasedocs/LWD/LWD_DeflectionMethod_051209re.pdf. Accessed July, 2011.

National Lime Association (2000). “Guidelines for stabilisation of soils containing sulfates” Texas, USA, < http:// www.lime.org/documents/ publications/ free_downloads/technical-memorandum.pdf >, (August 15, 2010).

National Highway Institute (NHI). (1994). *Pavement Deflection Analysis.* FHWA-94-012. NHI Course No. 13127. National Highway Institute, Arlington. V.A.

New Mexico Department of Transportation (2007). “Section 306: Portland Cement or Lime Treated Subgrade.” *Standard Specifications for Highway and Bridge Construction.*

New York State Department of Transportation (2010). “Section 302 - Bituminous Stabilized Course, Section 307 - Hydrated Lime Stabilized Subgrade.” *Standard Specifications,* Albany, New York

NCHRP. (2008). *Falling Weight Deflectometer Usage.* Synthesis 38. National Cooperative Highway Research Program, Transportation Research Board of the National Academies.

NCHRP. (1996). *Measuring in-situ mechanical properties of pavement subgrade soils* Synthesis 278, National Cooperative Highway Research Program. Transportation Research Board of the National Academies. P.27

North Carolina Department of Transportation (2002). "Section 501-Lime-Treated Soil, Section 540-Cement Treated Base Course, Section 542-Soil-Cement Base." *Standard Specifications for Roads and Structures.*

Oklahoma Department of Transportation (2009). "Section 307-Subgraade Treatment." *Construction Engineering Standards, Specifications, Materials and Testing.*

Oflaherty, C.A., Charles, E. E., and Davidson, D. T. (1963) *the Iowa State Compaction Apparatus: a Small Sample Apparatus for Use in Obtaining Density and Strength Measurements of Soil and Soil-Additives.* Project HR-83 of the Iowa State University Board, for presentation at the Forty Second Annual Meeting of the Highway Research Board, Washington, D. C.

Parsons, R. L., Kneebone, E., and Milburn, J. P. (2004). *Use of cement kiln dust for subgrade stabilization.* Rep. No. KS-04-3, Kansas Department of Transportation, Kansas.

Parsons, R. L., and Kneebone, E. (2005). "Field performance of fly ash stabilised subgrades." *Ground Improvement*, 9(1), 33–38.

Pennsylvania Department of Transportation (2006). "Item 9210-2022- Subgrade Treatment." *Standard Special Provision.*

Petry, T. M., and Das, B. (2001). "Evaluation of Chemical Modifiers and Stabilizers for Chemically Active Soils-Clays." *Transportation Research Board*, 1757, 43-49.

Petry, T. M., and Little, D. N. (2002). "Review of stabilization of clays and expansive soils in pavements and lightly loaded structures- History, practice, and future." *Journal of Materials in Civil Engineering*, 14(6), 447-460.

Portland Cement Association (1995). *Soil-Cement Construction Handbook*, Skokie, Illinois.

Qubain, B. S., Seksinsky, E. J., and Li, J. (2000). "Incorporating subgrade lime stabilization into pavement design." *Transportation Research Record*, 1721, 3-8.

Qubain, B. S., Heirendt, K. M., and Li, J. (2006) "Quality Assurance and Quality Control

Requirements for Lime and Cement Subgrade Stabilization." *GSP-154: Pavement Mechanics and Performance*, Shanghai, China, 229-238.

Quintus, H. V., and Killingsworth, B. (1997). *Design pamphlet for the backcalculation of pavement layer moduli in support of the 1993 AASHTO guide for the design of pavement structures.* FHWA-RD-97-076. Office of Engineering Research and Development Federal Highway Adimistration, McLean, VA.

Rafalko, S. D., Filz, G. M., Brandon, T. L., and Mitchell, J. K. (2007). "Rapid Chemical Stabilization of Soft Clay Soils." *Transportation Research Record*, 2026, 39-46.

Rollings, M. P., and Rollings, R. S. Jr. (1996). *Geotechnical Materials in Construction.* McGraw-Hill, New York, NY, 249-312.

Sacomaine.org. (2000). *Standard Specifications for Construction of Site Improvements in the City of Saco.* <http://www.sacomaine.org/ departments/ publicworks/ construction/02245.pdf> (May 19, 2009).

Senol, A., Edil, T. B., Bin-Shafique Md. S., Acosta, H. A., and Benson, C. H. (2006). "Soft subgrades' stabilization by using various fly ashes." *Journal of Resources, Conservation and Recycling*, 46, 365–376.

Seyman, E. (2003). *Laboratory Evaluation In-situ Tests as Potential Quality Control/Quality Assurance Tools.* M.Sc. thesis submitted to Louisiana State University and Agricultural and Mechanical College, Baton Rouge, LA.

SHRP2 R02 Phase 1 Technology Assessments (2008). *Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform.* Transportation Research Board.

Smith, R. B. and Pratt, D. N. (1983). "A Field Study of In-situ California Bearing Ratio and Dynamic Cone Penetrometer Testing for Subgrade Investigation." *Australian Road Research*,13(4), pp 285-293.

Snedker, E. A. (1996). "M40 - Lime Stabilisation Experiences." *Lime stabilisation: proceedings of the seminar held at Loughborough University Civil & Building Engineering Department on 25 September*, C.D.F. Rogers, S. Glendinning, and N. Dixon, eds., Thomas Telford, London, 142-158.

Snethen, D. R. (2008). *Evaluation and Field Verification of Strength and Structural Improvement of Chemically Stabilized Subgrade Soil.* ODOT Reference Number 2195, OSU EN 06-RS-200. Oklahoma Department of Transportation, Oklahoma City, OK.

Solanki, P., Khoury, N., and Zaman, M. (2007). "Engineering behavior and microstructure of soil stabilized with cement kiln dust." *GeoDenver 2007, GSP-172: Soil Improvement*, February, Denver, Colorado, 1-13.

South Carolina Department of Transportation (2007). "Section 301-Cement Modified Subbase, Section 307-Cement Stabilized Earth Base, Section 308-Cement Stabilized Aggregate Base." *Standard Specifications For Highway Construction*, Columbia, South Carolina.

Syed, I. M., Fuselier, G. K., and Hewitt, M. (2007). "Innovation in Cement Stabilization of Airfield Subgrades." *2007 Faa Worldwide Airport Technology Transfer Conference,* April, Atlantic City, New Jersey, 1-12.

Takallou, M. B., Layton, R. D., Hicks, R. G., and Lund, J. (1987a). "An Overview of Alternate Surfacings for Forest Roads." *Transportation Research Board*, 1106, 1-10.

Takallou, M. B., Layton, R. D., and Hicks, R. G. (1987b). "Evaluation of Alternatives Surfacings for Forest Roads." *Transportation Research Board*, 1106, 10-22.

Tennessee Department of Transportation (2006). "Section 302-Subgrade Treatment (Lime), Section 304-Soil-Cement Base, Section 307-Bituminous Plant Mix Base (Hot Mix), Section 309-Aggregate-Cement Base Course, Section 312-Aggregate-Lime-Fly Ash Stabilized Base Course." *Standard Specifications For Road And Bridge Construction.* Nashville, Tennessee.

Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., and Thompson, M. R. (1979). *Soil stabilization in pavement structures: A user's manual*. FHWA-IP-80-2, Vol. I and II, Department of Transportation, Federal Highway Administration, Washington, D.C.

Terzaghi, K., 1955 "Evaluation of Coefficient of Subgrade reaction," Geotechnique, Vol. 5, No.4, pp. 297-326.

Texas Department of Transportation (2004). “Item 260-Lime Treatment (Road-Mixed), Item 265-Fly Ash Or Lime—Fly Ash Treatment (Road-Mixed), Item 275-Cement Treatment (Road-Mixed), Item 276-Cement Treatment (Plant-Mixed).” *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*.

Thompson, M. R. (1970). “Suggested Methods of Method of Mixture Design for Lime-Treated Soils.” *SPT, American Society for Testing and Materials.*

Thompson, M. R. (1988). “Admixture stabilization of Subgrades.” *Proceedings of Ohio River Valley Soils Seminar XIX*, October, Lexington, Kentucky, 1-1-1-13.

Thuma, R. G. (1995). *Green's Function Analysis of Pavement Deflections Due to Moving Wheel Loads.* Report Number 96-020. Department of the Air Force, OH.

Transportation Research Board (1987). *Lime Stabilization: Reactions, Properties, Design and Construction.* State of the Art Report 5, Report prepared by TRB Committee on Lime and Lime-Fly Ash Stabilization, Washington, D.C.

Trzebiatowski, B. D., Edil, T. B., and Benson, C. H. (2004). “Case Study of Subgrade Stabilization Using Fly Ash: State Highway 32, Port Washington, Wisconsin.” *Recycled Materials in Geotechnics: Proceedings of Sessions of the ASCE Civil Engineering Conference and Exposition*, 123-136.

Virginia Department of Transportation (2007). “Section 306—Lime Stabilization, Section 307—Hydraulic Cement Stabilization, Section 313—Asphalt-Stabilized Open-Graded Material.” *Road and Bridge Specifications*, Richmond, Virginia.

Vennapusa, P. K., and White, D. J., (2009). “Comparison of Light Weight Deflectometer Measurements for Pavement Foundation Materials.” *Geotechnical Testing Journal*, Vol. 32(3), West Conshohocken, PA, 239-251.

Vitton, S. (2008). Guidelines and Best Practices for Selecting the Proper Subgrade/Base Stabilization Alternatives,<*http://www.northcenlpavment.org/docs/Soil_Stabilization.*

ppt> (August 16, 2009).

Voor, B. H., and Newton, E. H. (1988). "Case History of a Cement Stabilized Coal Transfer Yard." *Proceedings of Ohio River Valley Soils Seminar XIX*, October, Lexington, Kentucky, 2-1-2-9.

Webster, S. L., Grau, R. H., and Williams, R. P. (1992). *Description and Application of Dual Mass Dynamic Cone Penetrometer*. Instruction Report No. GL-92-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Webster, S. L., Brown, R. W., and Porter, J. R. (1994). "Force Projection Site Evaluation Using the Electrical Cone Penetrometer (ECP) and the Dynamic Cone Penetrometer (DCP)." *Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields*, University of Minnesota, Minneapolis, MN.

White, D. J., Harrington, D., and Thomas, Z. (2005). *Final Report-Fly Ash Soil Stabilization for Non-Uniform Subgrade Soils*, Vol I: Engineering Properties and Construction Guidelines, Iowa State University, Iowa.

White, D. J., Vennapusa, P. K. R., and Thompson, M. J. (2007). *Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials*. Partnership for Geotechnical Advancement (PGA) Tech Transfer Summary. Iowa State University, Ames, http://www.ctre.iastate.edu/pubs/t2summaries/intel_compaction.pdf . Accessed May 18, 2009.

White, D. J., Vennapusa, P., and Wolfe, A. J. (2010) *Jointed Concrete Pavement Rehabilitation with Injected Polyurethane Foam and Dowel Bar Retrofitting – US422 Field Study*. Earthworks Engineering Research Center, Institute for Transportation, Iowa State University.

Winterkorn, H. F., and Pamukcu, S. (1990). *Soil stabilization and grouting*. Foundation Engineering Handbook, Chapter 9, Ed. By Fang, Hsai-Yang, 2nd Edition, Van Nortrand Reinhold, New York, 317-349.

Wyoming Department of Transportation (2003). "Section 214-Lime Treated Subgrade," *Standard Specifications for Road and Bridge Construction*, Cheyenne, Wyoming.

Yesiller, N., Hanson, J. L., Rener, A. T., and Usmen, M.A. (2001). "Ultrasonic Testing for Evaluation of Stabilized Mixtures." *Transportation Research Board*, 1757, 32-39.

Yusuf, F. A. M. S., Little, D.N., and Sarkar, S. L. (2001). "Evaluation of Structural Contribution of Lime Stabilization of Subgrade Soils in Mississippi." *Transportation Research Board*, 1757, 22-31.

Zimper, W. H. (1961). "Plate Bearing Tests and Flexible Pavement Design in Florida." *Highway Research Board Bulletin*, Highway Research Board.

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APPENDIX A: TASK 9 COMPREHENSIVE TECHNOLOGY SUMMARY

31. CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES

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A research project titled "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform" is sponsored by the Strategic Highway Research Program (SHRP2). The project includes three elements: (1) new embankment and roadway construction over unstable soils, (2) roadway embankment widening, and (3) stabilization of pavement working platforms. Project details are described in the Phase 1 project report. As part of Phase 2, Comprehensive Technology Summary (CTS) documents are being prepared for over 40 ground improvement technologies. The CTS documents are working documents that contain source material for completing the Phase 2 tasks, and they will be updated as the project progresses. Each CTS consists of the sections listed in the following table of contents. Some of the sections are labeled with task numbers that correspond to components of Phase 2. A complete reference matrix and bibliography for this technology is contained in a separate document.

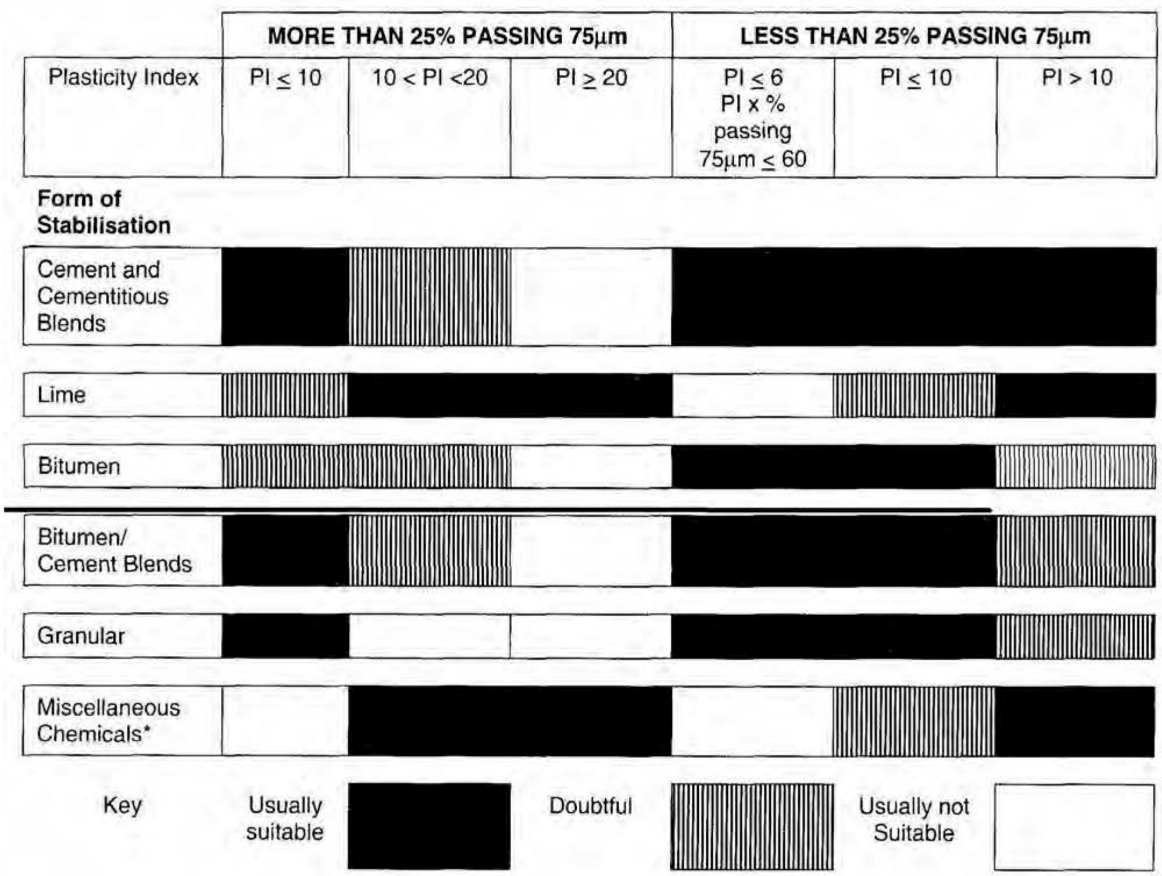
CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TECHNOLOGY DEFINITION/DESCRIPTION

Admixtures, such as lime, cement, fly ash, and asphalt, have been mixed with subgrade soils to control the swelling and frost heave and improve the strength characteristics of problematic soils. For stabilization or modification of cohesive soils, hydrated lime is the most widely used admixture. Lime is applicable in plastic clay soils (CH and CL type soils) and in granular soils containing clay binder (GC and SC), while Portland cement is more commonly used in non-plastic soils. Lime reduces the Plasticity Index (PI) and renders a clay soil less sensitive to moisture changes. The use of lime should be considered whenever the PI of the soil is greater than 12. Lime stabilization is used in many areas of the U.S. to obtain a good construction platform in wet weather above highly plastic clays and other fine-grained soils. It is important to note that changing the physical properties of a soil through chemical stabilization can produce a soil that is susceptible to frost heave. The following is a brief description of the characteristics of stabilized soils followed by the treatment procedures. Additional guidance on soil stabilization with admixtures can be obtained from the following resources:

Chemical Stabilization Methods for Pavements (after Rollings and Rollings, 1996).

Stabilization Method	Soil Type	Subgrade Improvement	Remarks
Portland cement	Plastic	Similar to lime Cementing of grains	Less pronounced hydration of cement
	Coarse	Cementing of grains	Hydration of cement
Lime	Plastic	Drying Strength gain Reduce plasticity Coarsen texture Long-term pozzolanic cementing	Rapid Rapid Rapid Rapid Slow
	Coarse with fines	Same as plastic	Dependent on quantity of plastic fines
	Non-plastic	None	No reactive material
Lime-fly ash	Same as lime	Same as lime	Covers broader range
Lime-cement- fly ash	Same as lime	Same as lime	Covers broader range
Bituminous	Coarse	Strengthen/bind waterproof	Asphalt cement or liquid asphalt
	Some fines	Same as coarse	Liquid asphalt
	Fine	None	Can't mix
Pozzolanic & slags	Silts and coarse	Acts as a filler cementing of grains	Dense and strong slower than cement
Chemicals	Plastic	Strength increase and volume stability	See vendor literature Difficult to mix

Guide for selection of admixture stabilization method(s) (Austroads 1998).



* Should be taken as a broad guideline only. Refer to trade literature for further information.

Note: The above forms of stabilisation may be used in combination, e.g. lime stabilisation to dry out materials and reduce their plasticity, making them suitable for other methods of stabilisation.

In the context of this SHRP2 program, chemical stabilization is the use of chemicals and emulsions as compaction aids to soils, as binders and water repellents, and as a means of modifying the behavior of clay (Das - TRB A2J02). Chemical stabilization of in-situ soils to a depth of 150 to 300 mm (6 to 12 inches) is a common practice. Depths greater than 300 mm (12 inches) generally requires removal and pugmill mixing (as typically done for base course and recycled materials), although rock trenching technologies can reportedly mix up to 0.6 to 1.2 meters (2 to 4 feet) with a single pass. Chemical stabilization technology is applicable to all soil types; however, specific chemicals and methods are recommended for different types of soils.

Although this technology applies to all elements of the SHRP2 program (as chemical stabilization can be used for construction of roadways over soft soil, widening of roadways, and the improvement of subgrade and base support), the focus of this technology assessment is with respect to subgrades and base course stabilization. Therefore, it is most applicable to SHRP2 R02 Element 3. Chemical stabilization is marginal in helping achieve Objective 1 (rapid renewal of traffic infrastructure) as it provides a faster means of improving soft subgrade over surcharge loading, allows the reuse of materials (e.g., recycled asphalt, concrete and base) which would normally require time consuming removal and disposal, but does require time for proper hydration and curing. Its primary benefit is in helping achieve Objective 3 (long-lived facilities), providing long lasting improvement for pavement working platforms and base materials. The current practice does not help achieve Objective 2 (minimal traffic disruption), again due to the time for curing; however, new construction methods such as use of trains to reconstruct pavement sections that incorporate chemical stabilization for recycled materials have accelerated construction and thus reduced traffic disruption.

The key obstacles preventing more widespread application of chemical stabilization are: (1) the absence of an allowance for improved stabilized subgrade support in current pavement design codes (e.g., AASHTO 1993, 1998); (2) dust produced by some processes; (3) absence of long-term performance data; and (4) negative marketing by opposing industry groups. While design methods exist for chemically stabilized bases, no allowance for improvement of subgrade support is provided in most pavement design codes. Of these, the main obstacle is confirming the long-term benefit though demonstration projects and forensics of existing sections where pavements have incorporated these technologies. A change in the U.S. design philosophy is also required where more effort is spent on the design of longer lasting roadway support, which will provide a performance period that is much longer than the surface pavements. Pavement engineers need to be educated on these technologies and design codes should include them as standard "best" practices.

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TASKS 9 AND 10C: TECHNOLOGY APPLICABILITY SCREENING PARAMETERS

The screening parameters outlined in this section will provide much of the raw material for Task 9, which is to develop a catalog of materials and systems for rapid renewal projects, and for the component of Task 10 to develop technology selection guidance. As described in the Phase 2 proposal, these screening parameters will be integrated into a comprehensive technology catalog and guidance system. This section allows for review and documentation of the different reported conditions for which this technology is most applicable. The parameters investigated include depth limits, soil types, groundwater conditions, project specific constraints, environmental considerations, equipment needs, approximate costs, potential advantages, potential disadvantages, and alternate solutions. References are listed alphabetically by author in each table below, as well as in subsequent sections of this comprehensive technology summary. If a page number is included in the "Reference" column, then it refers to the page number where the listed information was found in the reference. If information about a topic was not found in the literature, then the table entry for that topic is left blank.

Technology Overview Documents

Reported Data	Reference
Presents a technical overview of self-cementing fly ash stabilization, covering application, mix design, construction, and specification. The document can serve as a guideline of construction and design for self-cementing fly ash-stabilized soil.	ACAA (2008)
Provides a detailed description of different chemical admixtures used for stabilization and their applicability to pavement subgrade and base materials, design, construction, and QC procedures for different methods.	Army and the Air Force (1994)
Provides an overview of different chemical stabilization methods for pavement subgrade and base materials. Guidelines for construction, design, and QC/QA procedures, and application of different stabilizers with respect to soil type are discussed.	Austroads (1998)
This report provides a comprehensive overview on cement kiln dust in stabilizing clay soil, as well as a discussion characteristics of cement kiln dust, mechanism of stabilization, applicability to pavement subbase and base, and engineering properties of stabilized soils. This document can be served as a guide for selecting and using Cement Kiln Dust (CKD) to stabilize clay soils.	Bhatty et al. (1996)
Chapter 7 of the manual provides a comprehensive overview of different chemical stabilization methods used for pavement subgrade improvement and guidelines for design procedures. Chapter 8 provides guidelines for typical construction procedures for chemical stabilization of subgrade and base materials	Christopher et al. (2006)
Provides a comprehensive overview of lime stabilization covering details of mechanism, design, construction, QC/QA, specifications, and life cycle costs.	Little (1995)

Provides a 60-year historical background, overview, and state-of-the practice of chemical stabilization methods for plastic clay soils.	Petry and Little (2002)
Chapter 6 of this book provides a technology comprehensive overview with detailed descriptions of mechanisms, applications, design methods, and construction considerations of a variety of stabilizers.	Rollings and Rollings (1996)

Applications

Reported Data	**Reference**
Use of self-cementing fly ash is an effective method to improve the engineering properties of soil (e.g., strength, stiffness, and freeze-thaw durability), reducing shrink-swell potential of soil, and drying soil to facilitate compaction.	ACAA (2008), p. 11
Chemical stabilization methods are applicable to reducing PI or swelling potential, increasing durability and strength, providing a working platform for construction traffic in wet weather or weak soil conditions, and waterproofing.	Army and Air Force (1994), p. 2-1
Applicable to improving weak support conditions under construction traffic, reducing the pavement thickness, providing a cost-effective alternative to overexcavation/undercutting of existing pavement foundation layers on rehabilitation projects, reducing the moisture susceptibility, and providing a relatively strong and uniform working platform under construction traffic.	Austroads (1998), p. 12
Stabilization using cementitious admixtures is applicable to improving subgrade strength, providing a working platform for construction equipment, converting material of subgrade quality to that of subbase quality, reducing construction problems associated with variable subgrade strengths, and providing a water-resistant subbase for permeable or jointed pavements.	Austroads (1998), p. 28-29
Cementitiously-treated (e.g., using fly ash, lime, and pulverized blast furnace slag) base courses are applicable to improving strength of weak materials and reducing their moisture sensitivity.	Austroads (1998), p. 29
Cement kiln dust and fly ash mixtures are applicable to stabilizing subbase materials. This stabilization method improves strength, durability, and other engineering properties of subsoils, which can be a substitutable method for cement or lime stabilization.	Bhatty et al. (1996), p. 3
Lime stabilization method is effective in improving workability and reducing swell potential of highly plastic clay soils.	Christopher et al. (2006), p. 7-79
Lime-cement stabilization method is effective in improving soil workability characteristics.	Christopher et al. (2006), p. 7-89

Soil Types

Reported Data	Reference
Both cohesive soils and granular materials are suitable for self-cementing coal fly ash stabilization method.	ACAA (2008), p. 15
Lime and cement mixtures are applicable to high plasticity clay soils	Addison and Polma (2007), p. 9
Portland cement stabilization is effective for well-graded granular materials. Fly ash is suitable for soils that contain no or little plastic fines. Asphalt stabilization is suitable for silt, sandy, and granular soils.	Army and Air Force (1994), p. 2-1
The laboratory study showed that CKD stabilization is applicable to expensive clays.	Bhatty et al. (1996), p. 4
Lime stabilization may be used to treat expansive soils with a PI greater than 12 and with a minimum 10% passing the No. 40 sieve. Cement stabilization is applicable for low-plastic clay soils with PI less than 20, sandy soils, and granular soils. Lime-fly ash and lime-cement-fly ash admixtures are applicable for coarse-grained soils. Bituminous stabilization is not recommended for soils with percent fines (passing No. 200 sieve) greater than 20 percent.	Christopher et al. (2006), p. 7-79
Treatment with Type II or Type V cement stabilizer may minimize the problems with sulfate bearing soil.	Rollings and Rollings (1996), p. 278
Asphalt stabilization is suitable for granular materials.	Rollings and Rollings (1996), p. 298
Mixture of lime–fly ash is effective in treating silty soils.	Rollings and Rollings (1996), p. 303

Groundwater Conditions

Reported Data	Reference
Compaction operations may cause water to be pumped to a surface for silts and very-fine-sand subgrades because of a high water table in the area.	Air Force Joint Pamphlet (1994), p. 6

Depth Limits

Reported Data	Reference
Chemical stabilization mixed with in-situ soils to a depth of 150 to 300 mm (6 to 12 inches) is common. Depths greater that 12 inches generally require removal and pugmill mixing (as is usually done for base course and recycled materials), although rock trenching technologies can reportedly mix up to 0.6 to 1.2 meters (2 to 4 feet) with a single pass.	SHRP2 Phase 1 Technology Assessment 2008
Typically, lime stabilization can perform up to the depth of 0.6 to1 meters (2 to 3 feet) without removal/overexcavation of the soil.	Christopher et al. (2006), p. 7-79

<table>
<tr>
<td>The recommended minimum thickness of lime/cement-fly ash-soil and fly ash-soil mixtures are presented in below:
<table>
<tr><th>Application</th><th>Recommended Minimum Thickness cm (inches)</th></tr>
<tr><td>Base Course</td><td>15.2 (6)</td></tr>
<tr><td>Subbase Course</td><td>10.2 (4)</td></tr>
<tr><td>Subgrade Modification</td><td>10.2 (4)</td></tr>
</table>
</td>
<td>EPRI (1992), p. 6-23</td>
</tr>
</table>

Material Properties of Improved Soils

Reported Data	Reference
From the results of field projects throughout the Midwest, it shows that (1) compaction delay for fly ash stabilization of soils results in a smaller improvement of unconfined compressive strength of soils. With a 2-hour compaction delay, typically the stabilized soils exhibit unconfined strengths 3 to 5 times greater than the untreated soils, comparing with 6 to 12 times with no compaction delay, (2) the saturated CBR of pavement subgrade increases from 2 to 3 for untreated clay soils to 25 to 30 for the fly ash-stabilized subgrade, (3) fly-ash stabilized aggregate base can have a maximum 7-day compressive strength in excess of 5.52 MPa (800 psi), and (4) the swell potential of fly ash-stabilized soils is typically less than 0.5% under compressive strengths of 4.8 kPa (100 psf).	ACAA (2008), p. 31
It is reported that using various combinations of lime-cement admixture increased the subgrade durability by about 4.8 to 5.7 times, after one year of exposure to in-place conditions. Controlled laboratory tests showed that the 28-day moist cured saturated samples showed improved compressive strengths by about 3.7 times, and for samples following 12 cycles of wetting and drying showed improved strengths by about 3.5 times.	Addison and Polma (2007), p. 1
It is stated herein that USACE (1990) recommends that the base course material should have minimum unconfined compression strength of 5170 kPa (750 psi).	Aiban et al. (1998), p. 336
Typical elastic modulus for well-graded cement-treated base materials range from 2,000 to 20,000 MPa (290 to 2900 ksi).	Austroads (1998), p. 25

Provides the laboratory results on CKD stabilizing for expansive clays (the soil group was CH classified by Unified Soil Classification System), it showed that the unconfined compressive strength of the treated clay can reach 338 kPa (49 psi) for samples cured for 56 days with 25% CKD. The plasticity index of raw clay was 64% and 12.1% for samples cured for 56 days with 40% CKD. According to ASTM D 4546 procedure, the tested swelling of the clay was reduced from 9% as the raw clay to 0% after treated with 25% CKD. The bearing capacity of the treated soil from CBR tests increased substantially with CKD contents varied from 5% and 20%. Similarly, the engineering properties (unconfined compressive strength, plasticity, and wetting-drying durability) of 50:50 Kaolinite-bentonite mixture, kaolinite, and bentonite clay improved using CKD stabilization.	Bhatty et al. (1996), p. 6
Presents laboratory test results of lime and fly ash stabilization methods for highly plastic clay. The relationship between shrinkage reduction and percentage of additive is plotted showing that the value of shrinkage reduction increases with the increasing percentage of additive.	Buhler and Cerato (2007), p. 7
Typical unconfined compressive strength of lime (3 to 8% of the dry weight of the soil) stabilized clay soils is at least 0.34 MPa (50 psi) within 28 days. Typical unconfined compressive strength of cement (3 to 10% of the dry weight of the soil) stabilized granular soils is at least 1 MPa (145 psi) at 7 days.	Christopher et al. (2006), p. 7-80-7-84
This reference provides in-situ CBR and SPT N-values in tables for various stabilized subgrade field projects in Kentucky. Chemical admixtures used on the field projects included hydrated lime, Portland cement, fly ash, and lime kiln dust. Comparisons between stabilized and un-stabilized in-situ subgrade CBR values are provided.	Hopkins et al. (2002), p. 11-44
Provides in-situ and laboratory test results of soil engineering properties of lime-stabilized soils and aggregates. Generally, as lime content and/or curing days increase, the compressive strength and undrained shear strength of the stabilized material increase. Increasing lime content typically decreases the swell pressure. Unconfined compressive strength of a lime-stabilized plastic soil can achieve at least 345 kPa (50 psi).	Little (1995b), p. 75-121
This report presents laboratory test results of using cement kiln dust for subgrade stabilization (plastic and non-plastic soils). The results shows that (1) strength and stiffness of soils are improved; (2) plastic and swell potential of soils are reduced. Freeze thaw and leaching test results are provided as well.	Parson et al. (2004), p. 1-50

Presents laboratory tests of the effectiveness of CKD in stabilization. The properties (resilient modulus, modulus of elasticity and unconfined compressive strength) of soils stabilized with different percentages of additive (5%, 10% and 15%) are investigated in this study. The study results show the values of resilient modulus, modulus of elasticity and unconfined compressive strength increase with CKD amount.	Solanki et al. (2007), p. 3-9

Material Properties of Additives and/or Inclusions

Reported Data	Reference
Ash as an additive is classified as three types (1) very self-cementing fly ash: compressive strengths greater than 345 MPa (500 psi) at seven days, (2) moderately self-cementing fly ash: compressive strengths equal to or greater than 70 MPa (100 psi), but less than or equal to 345 MPa (500 psi) at 7 days, and (3) non-self-cementing fly ash: compressive strength less than 70 MPa (100 psi) at 7 days, according to ASTM D 5239 and ASTM Test Method C109/C109M (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 50-mm (2-in) Cubic Specimens). Fly ash has a typical particulate size ranging from less than 1 μm to greater than 1 mm.	ACAA (2008), p. 12
Descriptions of several different types of cement stabilizers (e.g., Type I, II, III classified in accordance with ASTM C 150) are presented in this reference.	Christopher et al. (2006), p. 7-84
Chapter 2 of this reference provides chemical and physical properties (e.g. specific gravity and bulk density, particle size, pH of lime-water solutions, and reaction of lime with carbon dioxide) of quick and hydrated lime. The bulk density of quicklime ranges from 768 to 1120 kg/m^3 (48 to 70 lb/ft^3). Typically, the solubility of lime in distilled water decreases as the temperature increases.	Little (1995b), p. 11-15
Properties including specific gravity, percent fines, moisture content, loss of ignition, calcium, and other oxides are presented for four types of fly ash.	Senol et al. (2005), p. 367
Presents engineering properties of fly ash, including X-Ray analysis, fly ash set time, fly ash paste strength, grain size distribution, and moisture-density relationships.	White et al. (2005), p. 35-43

Project Specific Constraints

Reported Data	Reference
Fly ash stabilization of fat clay soils results in an increase in permeability that may increase frost heave potential of the soils.	ACAA (2008), p. 31
Compactions of the pulverized and blended mixture is required to be completed as soon as possible following the final pass of the mixing equipment for achieving the maximum potential degree of stabilization.	ACAA (2008), p. 45

The effectiveness of lime and cement stabilization of soils is limited by the temperature sensitivity of stabilizers.	Daniels and Janardhanam (2007), p. 2
Severe pavement damage may occur due to expansive minerals formed from the reaction of calcium-based materials used to stabilize sulfate-bearing soils.	Kota et al. (1996), p. 62

Environmental Considerations

Reported Data	Reference
The position of self-cementing ash-stabilized material should be maintained above the groundwater table in order to limit water flow to maintain the engineering properties of the stabilized soil.	ACAA(2008), p. 52
Heavy rainfall, wet soils and cold weather conditions during construction can affect the properties of stabilized soils. Special construction procedures (e.g., providing a good crown and surface grade to permit rapid runoff of surface water before soil-cement processing to against excessive amounts of wet material) that may be used under those circumstances are provided in this reference.	Army and Air Force (1994), p. 4-10
The use of existing material reduces the need for backfill. Industrial by-products can be used as chemical stabilizers. In-situ stabilization is less disruptive to traffic and reduces hauling of materials leading to reduction in vehicle emissions.	Austroads (1998), p. 10
The use of dry-hydrated lime may cause dust control problems.	Christopher et al. (2006), p. 8-34
Some chemical admixtures (Portland cement, lime, and fly ash) may contain hazardous materials. The safety precautions for using and handling these admixtures are presented.	Dept. of the Army (1992), p. C-1-C-5
The air temperature during chemical stabilization process should be greater than 7.2° C (45° F).	Hopkins et al. (2002), p. 8

Equipment Needs

Reported Data	Reference
The transportation of fly ash is accomplished with pneumatic tankers or bottom dump trailers. Using a vane feeder hopper truck is good at controlling the fly ash application rate. Pulverization and mixing of fly ash with soils can be completed with one or two passes of a pavement recycler or rotary mixer. A vibratory pad-foot roller provides the initial compaction of the stabilized mixture. After the initial compaction, a self-propelled, pneumatic-tired roller is applied to final grade the materials for blading and final compaction.	ACAA(2008), p. 45

Different types of equipment used for mixing, handling, and spreading of admixtures (i.e., Portland cement, lime and bitumen) are presented. Safety recommendations are provided in the reference for use of protective equipment for eyes, mouth, nose, and skin, and a first-aid kit containing an eyeball wash on stabilization project sites.	Army and Air Force (1994), p. 4-14
Equipment needed for preparation, handling, mixing and water application, compaction, finishing, and curing of Portland cement stabilized subgrade soils are discussed.	Portland Cement Association (1995), p.18
Rotary-drum central mixing plants work poorly for soils with plastic fines. Non-plastic or slightly plastics soils are mixed using windrow-type traveling mixers. The transverse rotary mixers can be used for a wide range of soils (plastic to non-plastic); however, plastic soils may need multiple passes. Slightly plastic soils are suitable for processing in revolving-blade central mixing plants. Twin-shaft pugmills work vigorously for a wide range of soils (plastic to non-plastic).	Rollings and Rollings (1996), p. 283

Potential Advantages

Reported Data	Reference
Mixing clay soils with lime allows for clay clods to be easily broken down during pulverization, reduces PI, reduces water absorption and swelling potential, and increases strength with time.	Addison and Polma (2007), p. 4
Base courses treated with cementitious materials are beneficial for low-strength roads with heavy traffic. It improves the load carrying capacity of a pavement for areas subjected to frequent flooding and where life-cycle costs can be minimized.	Austroads (1998), p. 29
The use of combinations of cementitious and mixtures of bituminous binders has shown success in increasing cohesion and reducing moisture susceptibility as well as improving strength.	Austroads (1998), p. 38
Use of CKD stabilization can potentially open a large market for waste material from cement plants, which produces nearly 5 million tons of CKD in North America every year.	Bhatty (1996), p. 1
Lime modification of subgrade soils can expedite construction and no reduction occurs in the required pavement thickness.	Christopher et al. (2006), p. 7-78
Chemical stabilized subgrades withstand excessively large water pressures from the load induced by traffic and keeps subgrade pumping to a minimum.	Hopkins et al.(2002), p. XIX
It is stated herein that chemical stabilization of subgrade has the following advantages: (1) improving subgrade durability; (2) improving the bearing strength of subgrade soils; (3) increasing the stiffness of the subgrade soils; (4) decreasing the swell potential of subgrade soils; (5) expediting construction, and (6) poor engineering subgrade soil can be used effectively (Terrel et al., 1979).	Hopkins et al. (1995), p. 8

Compared with most pavements 10 or more years old, pavement over the cement-treated subgrades is much more resistant to rutting and other distortions.	Hopkins et al. (1994), p. 45
Soils stabilized with Class C fly ash, which is a drying agent and which of itself has a small volume change during the stabilization process, can gain strength very quickly serving as a working platform.	Parsons and Kneebone (2005), p. 33
Advantages of materials stabilized with fly ash or slag include that it is cheaper, has less permeability problems and reflective cracking, and is more resistant to sulfate attack with less durability problems than Portland cement.	Rollings and Rollings (1996), p. 302

Potential Disadvantages

Reported Data	Reference
Changing the physical properties of a soil through chemical stabilization can produce a soil that is susceptible to frost heave.	SHRP2 Phase 1 Technology Assessment 2008
Typical cement-modified soils require a higher percentage of cement and a thorough mixing of cement and soil compared with lime modification; also pulverization with cement is more difficult than with lime. For lime-modified soils, disadvantages include: modification and strength qualities reverse through leaching or moisture migration if less than adequate amounts of lime are used, permeability increases without using an adequate amount of lime, and a longer time is required to gain strength than cement modified soils.	Addison and Polma (2007), p. 4
Plastic soils that are not treated properly with lime can have durability problems when subjected to thawing, and cyclic freezing. Environmental conditions (e.g., cold weather, heavy rain, etc) can adversely affect the swell potential and strength properties of lime stabilized plastic clay soils.	Christopher et al. (2006), p. 7-84

Alternate Solutions

Reported Data	Reference
An alternative approach is mechanical stabilization of subgrades through mixing of aggregate with fine-grained clay subgrade materials.	Hopkins et al. (1995), p. 41
A combination of geotextiles and geogrids can be an alternative to chemical stabilization of plastic soils with soluble sulfates. If a soil is not highly plastic clay, geogrid may be used alone.	Kota et al. (1996), p. 68
Dynamic compaction, paper sludge, and blast densification can be used as alternatives for chemical stabilization of subgrades and base courses.	Vitton (2008), p. 51

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES:
TASKS 9 AND 10C: CASE HISTORY DATABASE

The case studies presented in this section will be an important part of Task 9, which is to develop a catalog of materials and systems for rapid renewal projects. Each case study appears in a standard format to allow for an efficient gathering of pertinent information. The information reported for each case study is as follows: the technologies used, a general project description, the date and duration of the project, the approximate size of the project, subsurface conditions, design details, construction details, QC/QA method used, short and long-term performance, problems encountered, project costs, other information about the project, and contact information provided by authors. This section compliments the literature database and will provide the end-user with a valuable resource in evaluating potential technologies for a project.

A Major Road, Dammam, Saudi Arabia	
Technologies used:	Chemical Stabilization of Subgrades and Base Courses
General Project Description:	In eastern Saudi Arabia, calcareous sediments, locally known as marl, were used in foundations and in base-course construction of roads and highways. The road performance was influenced by (1) the sensitivity of the base course material to water, (2) the shallow water table, and (3) the harsh loading conditions. A major road in Dammam industrial area, eastern Saudi Arabia was reported for frequent deterioration. The reconstruction of the road was conducted using chemical stabilization of base course in January 1994.
Date/Duration:	January 1994
Project Size:	N/A
Subsurface Conditions:	The soil containing marl was obtained at a depth of 10 to 12 meters (32.8 to 39.4 feet) at the location, 120 km (74.6 miles) from Dammam. The soil was classified as GP according to the USCS system. Subsurface conditions include distinct layers of soft and sound limestone, pure and relatively loose sand, loose and chalky white materials, voids with black internal coating, as well as other similar features.
Design Details:	Both eastbound and westbound lanes contained one stabilized section and one untreated section. In each direction, the stabilized section was adjacent to the untreated one. In total, 4% cement was selected for stabilization.
Construction Details:	Each stabilized section was 30 meters (98.4 feet) long. A 200 mm (8 inch) thick base course was maintained for all sections. Subgrade materials were compacted to about 95% of the maximum dry density. Compaction was conducted for a period of 2 to 3 hours after mixing the cement with the soil. Water was sprinkled over the stabilized base twice a day for the following 2 days.
QC/QA Methods:	Clegg impact values were recorded immediately following compaction and 24 hours after compaction. The value of CBR can be converted from the Clegg impact value.
Short and Long Term Performance:	The monitoring of the pilot program lasted 4 years. The performance of the constructed section was monitored using a dynaflect apparatus in the field and visual inspection. The obtained resilient moduli of the untreated and treated section were compared showing the cement-treated sections were more stable than the untreated ones during 4 years of service. After 4 years of service, the cement treated bases showed no evidence of deterioration.
Problems Encountered:	
Cost:	
Other:	
Source:	Aiban et al. (1998)
Contact Information Provided By Authors:	

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Cost:	
Other:	
Source:	Aiban et al. (1998)
Contact Information Provided By Authors:	

KY Route 11, Kentucky	
Technologies used:	Chemical Stabilization of Subgrades and Base Courses
General Project Description:	A portion of KY route 11, located 11.7 km (7.3 miles) north of Beattyville, Kentucky, was about 9.6 km (6 miles) in length. Four types of chemical stabilization (AFBC, cement, hydrated lime, multi-cone kiln dust) of subgrade were conducted in this portion of route, which was divided into seven sections that consisted of one unstablized section and six chemical stabilized sections. The study presented in this paper focus on analyzing the feasibility of the Atmospheric Fluidized Bed Combustion (AFBC) byproduct as the stabilization agent for two sections.
Date/Duration:	1986-1988
Project Size:	Two subgrade sections, 1.74 km (1.08 miles) and 1.35 km (0.84 miles).
Subsurface Conditions:	The subsurface consisted of interbedded layers of shales, sandstones, and coal. Liquid limit and plasticity indices of natural soils were in a range of 36 to 43% and 12 to 15%, respectively. Approximately 70% of the particles passed the No. 200 sieve.
Design Details:	Unconfined compression tests were carried out on laboratory prepared specimens. The percentage of stabilizer was selected at the point when no increase or a slight increase occurred in unconfined compression strength with an increase of stabilizer percentage. 7% and 10% of the AFBC byproduct were selected for two sections.
Construction Details:	Two sections stabilized using the AFBC byproduct, measuring 1.35 km (0.84 miles) and 1.74 km (1.08 miles), were compacted met the dry density specification.
QC/QA Methods:	
Short and Long Term Performance:	In-situ CBR values ranged from 34 to 53 seven days after construction, and from 10 to 54 from October of 1987 to March 1999. Overall, satisfactory performance was achieved over a 12-year period.
Problems Encountered:	Several heave or differential swellings occurred 2 months after construction of base courses on two AFBC-stabilized sections. The swelling of stabilized subgrades consisted of primary and secondary swelling. The maximum primary swell value ranged from 1.8 to 8.8 cm (0.7 to 3.5 inches). The secondary swell value was very small over a period 5 years.
Cost:	
Other:	This type of stabilization should be investigated through characterization of both the stabilizer and the soils involved before full-scale field work is performed.
Source:	Hopkins and Beckham (1999)
Contact Information Provided By Authors:	

Washington Dulles International Airport, Virginia	
Technologies used:	Chemical Stabilization of Subgrades and Base Courses
General Project Description:	The Washington Dulles International Airport is located in Virginia. In order to continue servicing the needs of the public, new facilities were built at the airport under the project called Dulles Development (d^2) Program. As a part of the program, 3,048 meters (10,000 feet) of runway was reconstructed with Portland cement concrete. Chemical stabilization for subgrades with cement was adopted.
Date/Duration:	
Project Size:	3,048 meters (10,000 feet)
Subsurface Conditions:	Ground water table varied between 23 cm and 304.8 cm (0.75 feet and 10 feet) below the existing pavement surface. Soaked CBR values for natural subgrade soils were found to be between 0.7 and 36.8.
Design Details:	Portland cement was selected as the additive to treat the top 300 mm (12 inches) of the existing subgrade. Several tests, including mechanical analysis, durability, shrinkage, and unconfined compressive strength test were conducted to select optimum cement content. Finally, a 4% cement content of the subgrade was used.
Construction Details:	
QC/QA Methods:	
Short and Long Term Performance:	
Problems Encountered:	
Cost:	
Other:	
Source:	Syed et al. (2007)
Contact Information Provided By Authors:	

A COAL TRANSFER YARD, KENTUCKY	
TECHNOLOGIES USED:	Chemical Stabilization of Subgrades and Base Courses
GENERAL PROJECT DESCRIPTION:	Chemical stabilization method was used to improve a subgrade to providing the working platform for the machinery load in a coal storage yard. However, failure of the soil-cement surface occurred at this site.
DATE/DURATION:	1986
PROJECT SIZE:	80,937 m^2 (20 acres)
SUBSURFACE CONDITIONS:	Recently deposited alluvium and glacial outwash deposits
DESIGN DETAILS:	A strength analysis was performed to select the proper additive and additive content. It was found that flexural strength increased greatly with 9% cement content sample. Then, a slab-like working surface was provided through: (1) soil mixing with 8% cement up to a thickness of 300 mm (12 inches), (2) in-situ blending of sand and gravel, and (3) compaction to 95% of the modified proctor maximum dry density.
CONSTRUCTION DETAILS:	The 300-mm (12-inch) layer of sandy gravel borrow was spread over the surface of the yard. Then, cement was spread over the sandy gravel layer. Thereafter, a single pass of machinery was utilized to mix cement into the sandy gravel for the upper 300-mm (12-inch) layer. Afterward, water was added to surface materials, and the upper 203-mm (8-inch) of the layer was blended. An additional pass was performed. The compaction was carried out in the next step.
QC/QA METHODS:	A small test pad was constructed for quality control.
SHORT AND LONG TERM PERFORMANCE:	Within 6 months after the storage area became operable, severe cracking and rutting occurred in several cement-stabilized areas.
PROBLEMS ENCOUNTERED:	The failures of the soil-cement pad might have several causes as follows: (1) insufficient soil-cement thickness to carry loads; (2) localized inadequate compaction of soil-cement surface; (3) non-uniform cement mixture; (4) non-uniform and inadequate compaction of subgrade; and (5) presence of organic matter.
COST:	The unit cost of all alternatives was evaluated.
OTHER:	One year after construction, rehabilitation was conducted without interruption of the facility operation.
SOURCE:	Voor and Newton (1988)
CONTACT INFORMATION PROVIDED BY AUTHORS:	

State highway 32, Port Washington, Wisconsin	
Technologies used:	Chemical Stabilization of Subgrades and Base Courses
General Project Description:	A sandy clay subgrade was stabilized using class C fly ash in Port Washington, Wisconsin as a construction platform for Portland Concrete Pavement.
Date/Duration:	
Project Size:	Stabilization was conducted in the two southbound lanes with a length of 3.7 km (2.3 mi) in State Trunk Highway 32. Five stations (611+50, 612+50, 613+50, 614+50, and 615+50) in a 150-meter (492-foot) segment of STH-32 were evaluated.
Subsurface Conditions:	According to ASTM D 2487, the nature soil was classified as sandy lean clay (612+50 and 615+50), clayey sand (614+50 and 613+50), or clayey gravel (611+50) with sand. The water content averaged 9.4% $\pm$ 1.6%.
Design Details:	Class C fly ash was provided by a power plant in Pleasant Prairie WI. Compaction and CBR tests were performed in laboratory for determine the proper fly ash content, which indicates that soil with 10% fly ash mixture can provide the best support for construction process. The stabilized subgrade was 0.3-meter (12-inch) thick with water content being 12 to 14%.
Construction Details:	Fly ash was spread onto the subgrade in a 0.1-meter (4-inch) thick layer using a lay-down truck. A road reclaimer was used for mixing the fly ash into the subgrade to a depth of 0.3 meters (12 inch), followed by compacting using 4-6 passes of a self-propelled tamping foot compactor. Then the surface was smoothed with a motor grader and compacted using a vibratory compactor with a steel drum. Compaction was continued until the target dry unit weight (18.8 kN/m^3 (120 lbs/ft^3)) was achieved, and was completed within 1 to 2 hours after mixing. Construction of the overlying pavement layer started 24 hours after the stabilization of soil.
QC/QA Methods:	A nuclear density gage was used to monitor the water content and dry unit weight during compaction.
Short and Long Term Performance:	A soil stiffness gauge was used to measure the stiffness for the surface of the stabilized subgrade. The improvement in stiffness was evaluated using falling weight deflectometer test. The laboratory test results showed that CBR ranged from 46 and 150 after 7-day curing. Resilient modulus of the stabilized soil ranged between 11 and 28 MPa (1595 and 4060 psi) after 7-day curing and between 17 and 68 MPa (2465 and 9860 psi) after 28-day curing. The in-situ stiffness of the stabilized soil was in a range of 9 to 31MN/m (617 to 2127 lbf/ft), comparing a range of 8 to 21 MN/m (549 to 1441 lbf/ft) for the unstablized soil. Unconfined compressive strength of soil was increased from a range of 276 to 607 kPa (40 to 88 psi) after 7-day curing to a range of 304 to 683 kPa (44 to 99 psi) after 28-day curing. Overall, fly ash stabilization of subgrade provides a good construction

	platform.
PROBLEMS ENCOUNTERED:	
COST:	
OTHER:	
SOURCE:	Trzebiatowski et al. (2004)
CONTACT INFORMATION PROVIDED BY AUTHORS:	

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TASK 10A: SUMMARY OF DESIGN PROCEDURES

This section provides short summaries of design procedures found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available procedures. The following references should be reviewed in more detail as part of Task 10, which includes development of design procedures for the technologies.

ACAA (2008)
Presents a general guideline for the laboratory mix design for fly ash stabilization method. The two objectives are to reduce the shrink-swell potential of soils, and use self-cementing ash as a drying agent. The first factor considered in the design of ash-stabilized material is the hydration rate of stabilized material. Moisture content can be another factor influencing the maximum compressive strength of the soil. At present, no standard test procedures exist for the design of soil stabilized with self-cementing ash. However, based on ASTM C593 (Fly Ash and Other Pozzolans for Use with Lime) and ASTM D1633 (Compressive Strength of Molded Soil-Cement Cylinders), the procedure is developed and effective in defining the optimum moisture content at which maximum compressive strength will be achieved.

Addison and Polma (2007)
This paper discusses how to determine the proper percent of either lime or combinations of lime and cement for the permanent modification of subgrades. Based on performance requirements, stabilization of subgrades with lime can be lime modification (for workability) or lime stabilization (for strength and durability). A series of pH tests are conducted to determine initial Lime Modification Optimum (LMO). Lime Stabilization Optimum (LSO) relies on the maximum shear strength that soil/lime mixtures can produce. Shear strength of compacted soil/lime mixtures are investigated through laboratory tests. Unconfined compression strength testing is carried out on the next step. Several limitations exist in selecting possible combinations of lime and cement for stabilization. After the selection of possible combinations, compressive strength analysis is performed on soil/lime/cement mixtures.

Aiban et al. (1998)
Presents a case study for chemical stabilization of subgrades in eastern Saudi Arabia. A design method is provided for the case study. Important factors affecting the selection of an admixture include: nature of the soil, workability of the mix, economic and safety constraints, conditions of construction, and environmental concerns. A series of laboratory testing is carried out to select cement content. Unconfined compressive strength and durability of stabilized samples are assessed through these tests.

Austroads (1998)
Design methods for chemical stabilization of subgrades and bases are provided for selection of stabilizing agents and mix design. For selecting a stabilizer, several factors should be considered, including: climate and drainage conditions (moisture content), pavement properties (e.g., thickness, traffic loads and volumes, and extent and variability of existing subgrade support), and

sampling and testing of materials (to assess feasibility of stabilizers before field work commences). Preliminary selection of a stabilizer is based on soil gradation and Atterberg limits. A table provides initial guidance to selecting a stabilizer. The important step of selection is comparing the life cycle costs among all alternatives. For mix design, important soil properties are addressed in design, covering strength (compressive and shear), durability, shrinkage characteristics, setting and curing characteristics, moisture susceptibility, erodibility, stiffness, fatigue performance (where applicable), and variability.

Christopher et al. (2006)
This document presents design methods for chemical stabilization methods (a single or combination type). The details of the design procedure and specific design requirements are presented in Appendix F.

EPRI (1992)
Presents guidelines for mix design of lime/cement-fly ash and fly ash methods for subgrades and base courses. The design factors taken into consideration are discussed including: (1) soil type, (2) fly ash type, (3) lime type, (4) proportion of stabilizers to soil, (5) ratio of lime or cement to fly ash, (6) dry density and moisture content of compacted mixture, (7) age of mixture, and (8) temperature.

Hopkins et al. (1988)
Develops a design method using unconfined compression testing to determine the optimum percentage of chemical admixtures in laboratory. Three typical methods are used to determine the optimum percentage of a chemical admixture: (1) unconfined compression tests, (2) charts and tables by manufactures of chemical admixtures, and (3) pH tests.

Terrel et al. (1979)
Presents a design guideline for lime, lime-fly ash, cement, asphalt, and combination stabilization (lime-cement, lime-asphalt, lime-emulsified asphalt, and cement-emulsified asphalt) method of subgrades and base courses stabilization. Volume I of this manual discusses a method for selection of the type of stabilizer and pavement thickness design for pavement design and construction engineers. Volume II of the manual describes methods for selecting the type and amount of stabilizers for materials engineers.

Chemical Stabilization of Subgrades and Base Courses: Task 10b: Summary of QC/QA Procedures

This section provides short summaries of QC/QA procedures found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available procedures. The following references should be reviewed in more detail as part of Task 10, which includes development of QC/QA procedures for the technologies.

Austroads (1998)
This manual describes QC/QA procedures and requirements for cementitious, lime, and bituminous stabilization methods for pavement subgrade and base materials. Testing is recommended during various phases of construction to check: (1) levels, profiles, and pavement shape; (2) mixing time or number of mixer passes; (3) depth of the stabilized layers both before and after compaction; (4) moisture content at various stages of construction; (5) performance of compaction procedures; (6) variability of existing material; and (7) wind speed for powder-type binders. Two common methods described for checking stabilizing agent application rates include: (1) spot checks for uniformity of rate of spread; and (2) total quantity check over the area stabilized.
A tray or a mat of known area on the surface and weighing the quantity of stabilizing agent deposited on it after spreading are used to control the application rate. Lime and cement contents of uncured mixtures are assessed by chemical analysis and X-Ray Fluorescence testing. Chemical analysis can be expensive and slow, however. Dipping of the tanker containing the stabilizer is used to determine the overall application rate of liquid spraying (for bituminous materials and lime slurries). Thickness of the loose layer is determined by probing and measurement with a ruler. Sampling and sieving of loose processed materials are used to check gradation of the materials and remove any oversized materials. Additive content tests are performed on cement and lime stabilized soils, while the tests are carried out both transversely across the pavement and at various depths within the stabilizer layer to assess the mixing effectiveness. A phenolphthalein test on a face cut in the stabilized layer is used as a “quick” test to determine the presence of lime or cement. Moisture content measurements are obtained before and after stabilization. Nuclear moisture-density gauges are used to obtain density of compacted stabilized layers.

Army and Air Force (1994)
This manual provides QC/QA methods for Chemical Stabilization of Subgrades and Base Courses with cement, lime, lime-fly ash, and asphalt in pavement construction. For controlling pulverization in cement stabilization, a sieve analysis is performed on the soil with No.4 sieve. Spot checking is performed to assure the proper quantity of cement is being applied. Moisture content is determined by nuclear methods. Uniformity is checked throughout the depth and across the width of the pavement. Trenches are dug and a visual inspection is made to assure uniformity of the mixture. Compaction density can be determined through several methods: sand-cone, balloon, oil, and nuclear methods. For lime stabilization, the application rate is checked by using a canvas of known area, as well as by field personnel using charts. Either a hydrometer or volumetric-weight procedure is used to determine the specific gravity of lime slurry to ensure that provides the desired amount of lime solids. The phenolphthalein indicator

solution is used to ensure the uniformity of mixing. Moisture content is determined by either oven-dry or nuclear methods. For bituminous stabilization, the surface moisture of the soil is determined using the same methods as lime stabilization. Visual inspection is performed to determine the uniformity of mixing of asphalt.

White et al. (2005)
Provides a review of QC/QA methods for the quality of completed sections of self-cementing fly ash-stabilized subgrade soils. These methods include field density and moisture, stability, and in-service performance-based tests.

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES:
TASK 11: COST INFORMATION

This section provides cost data for this technology from the sources that were reviewed in the literature database. The listed costs are those stated in the source; they are not adjusted for inflation. When available from the source document, separate entries are listed here for unit costs, mobilization and demobilization costs, and other cost components. If the costs are identified in the source as being from a single case history or from a collection of sources, that information is indicated here.

Reported Data	Reference
The construction cost varies with different additives. For a 6-inch deep subgrade preparation, the costs are approximately \$2.60/yd^2 with 7% lime, \$4.00/yd^2 with 14% lime, and \$4.63/yd^2 with combination 7% lime and 5% cement in the year 1999. The average cost of the typical subgrade treatment is \$4.81/yd^2 for the combination 5% lime and 7% cement in the years 2005 and 2006.	Addison and Polma (2007), p. 10
Chemical stabilization of subgrade — Unit Cost (dollars) Hydrated Lime-Soil 0.35 yd^2/in. Cement-Soil 0.49 yd^2/in. Lime Kiln Dust-Soil 0.30 yd^2/in. AFBC-Soil 0.30 yd^2/in.	Hopkins et al. (2002), p. 93
Using the amount of 12 to 16% Class C fly ash to treat subgrades, the unit cost ranges from \$3.30 to \$4.20/m^2.	Parsons and Kneebone (2005), p. 34
For chemical stabilization of subgrades, the average cost is typically \$1.74/yd^2 for a 6-inch stabilized layer.	Takallou et al. (1987a), p. 4

**CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES:
TASK 12: AVAILABLE SPECIFICATIONS**

This section provides information about specifications found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available specifications. The following references should be reviewed in more detail as part of Task 12, which is to develop sample guide specifications for these geotechnical materials and systems.

Little (1995)
This chapter provides guide specifications for chemical stabilization with lime for subgrades and base courses. The specification includes materials, submittals, standards, construction requirements, equipment limitations, safety requirements, and sampling and testing items. Payment method is not presented in this document.

Sacomaine.org (2009)
The website http://www.sacomaine.org/departments/publicworks/pol-construction.shtml provides a brief specification (section 02245) for chemical stabilization of subgrades in the city of Saco, Montana.

White et al. (2005)
The research develops construction guidelines and specifications for using self-cementing fly ash to stabilize soils, using hydrated or conditioned fly ash to stabilize soils, and using hydrated or conditioned fly ash as select fill under pavement structures. Laboratory evaluation, field placement, moisture conditions, compaction, quality control testing procedures, and basis of payment are described in these specifications.

TRB (1987)
A comprehensive listing of specifications and special provisions are presented. These specifications are provided by many agencies (e.g., AASHTO, U.S. Corps of Engineers and U.S. department of Transportation).

APPENDIX B: TASK 10 ASSESSMENT OF DESIGN METHODS AND QC/QA PROCEDURE

TASK 10 ASSESSMENT OF DESIGN METHODS AND QC/QA PROCEDURES
CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES

ASSESSOR(S): WENJUAN LI
ASSESSMENT REVIEWER(S): DAVID WHITE AND BARRY CHRISTOPHER
ADDITIONAL REVIEWER(S): IA, KS, AND OH DOTS
DATE OF THIS ASSESSMENT: JULY 20, 2011
FILE NAME FOR THIS VERSION: CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES TASK 10_06 2011_FORPEERREVIEW.DOC

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INTRODUCTION

BACKGROUND INFORMATION

Design procedures of one form or another already exist for many of the technologies that are being evaluated in the Strategic Highway Research Program's (SHRP2) research project R02, "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of Pavement Working Platform." Some technologies already have well-established design procedures, some have a variety of published design procedures, some have proprietary design procedures, and others have developing design procedures.

Some technologies have worthwhile analysis procedures that are not integrated into comprehensive design procedures. To avoid excluding such material, the design assessment sections of this document refer to both design and analysis procedures.

There are also many technologies for which establishing suitable QC/QA procedures is arguably the critical limiting factor preventing more widespread application of the technologies. Providing clear, precise, and effective guidelines for QC/QA procedures will remove an important source of uncertainty that currently makes some designers hesitant to apply these technologies.

DOCUMENT PURPOSE

This document provides instructions and a template for assessing and characterizing design/analysis procedures and QC/QA methods for technologies that are applicable to Element 3 of the SHRP2 R02 project. Element 3 addresses stabilization of the working platform. The assessments and characterizations in this document will be used to complete other work items associated with Task 10, as described in the Phase 2 work plan in the Phase 1 report.

DESCRIPTION OF DOCUMENT CONTENTS

The next two sections of this document provide instructions and a matrix for relating important inputs and outputs of design/analysis procedures to potential applications for the technology. These are organized in categories of performance criteria/indicators, subsurface conditions, loading conditions, material characteristics, construction techniques, and geometry. By identifying applicable input and output items first, assessors will be in a good position to evaluate design/analysis procedures.

The sections about design/analysis inputs and outputs are followed by two sections that provide instructions and a matrix for assessing published design/analysis procedures for this technology. These sections are followed by a section for detailed comments about each procedure, and then there are sections for characterizing the technology according to the status of its design/analysis procedures.

Sections for assessing the QC/QA methods follow a pattern similar to the design/analysis portion. The first section identifies objectives of QC/QA activities and relates them to potential applications of the technology. By first identifying QC/QA objectives, assessors will be in a good position to evaluate QC/QA methods. The QC/QA objectives should be closely related to the construction requirements produced as outputs of design procedures.

The section identifying QC/QA objectives is followed by two sections that provide instructions and a matrix for assessing published QC/QA procedures. These sections are followed by a section for detailed comments about each design procedure. Finally, there is a section for concluding remarks about QC/QA procedures in which the assessors can provide descriptions of the ways that individual QC/QA procedures can be integrated to form a comprehensive QC/QA program for a technology.

INPUTS AND OUTPUTS FOR DESIGN AND ANALYSIS PROCEDURES, INSTRUCTIONS

A matrix has been developed for listing inputs and outputs for analysis and design procedures. This section provides a description of the matrix and guidance for completing the matrix.

In the matrix, specific input and output items appropriate for a particular technology are arranged in the following categories: Performance Criteria/Indicators, Subsurface Conditions, Loading Conditions, Material Characteristics, Geometry, and Construction Techniques. Examples of specific items in each category are listed in the following table.

Categories of Input and Output Items for Analysis and Design Procedures	*Some Example Items*
Performance Criteria/Indicators	*Minimum factor of safety values, load and resistance factor values, allowable settlements, allowable lateral deformations, reliability, drainage, time*
Subsurface Conditions	*Stratigraphy, ground water level, particle size distribution, plasticity, unit weight, relative density, water content, strength, compressibility, chemistry, organic content, variability*
Loading Conditions	*Traffic load, embankment pressure, structure loads, earthquake acceleration and duration, water pressures*
Material Characteristics	*Unit weight, water content, particle size distribution, internal friction angle, shear strength, inclusion dimensions, compressive strength, tensile strength, compressibility, modulus, stiffness, interface friction angle, permeability, equivalent opening size*
Construction Techniques	*Vibration densification, impact densification, shoot in nails, screw in nails, paddle mixing, combined cutter and jet mixing*
Geometry	*Diameter, spacing, depth, thickness, length, slope*

The objective here is for assessors to develop a list of specific items that are appropriate inputs and outputs for analysis and design procedures for each application of this technology. The application categories relevant to Element 1 and 2 technologies are support of embankments, support of structures, earth retention, and slope stabilization. The assessors' list of input and output items should be inserted in the matrix, organized according to the categories provided.

The matrix is arranged without distinguishing whether a particular item is an input or an output because the same item might serve as an input to an analysis procedure and as an output of a design procedure. For example, the diameter and spacing of columns used to support an embankment are inputs to analysis procedures, but they can be considered outputs of design procedures. Similarly, the calculated factor of safety against slope instability is an output of an analysis procedure, and the required minimum factor of safety may be an input to a design procedure.

The Construction Techniques category is provided to accommodate technologies for which multiple techniques exist, such as gravel columns that can be compacted with vibrators or with impact rammers. For many technologies, only one construction technique is used or variations in construction technique do not impact design. In such cases, it is not necessary to have any entries in the Construction Techniques category.

After inserting the specific input and output items that are relevant for a particular technology, the assessor should indicate which items are relevant to which application.

The design/analysis performance criteria/indicators and specific items for static and dynamic analyses may not all be the same. Some items are used for both static and dynamic analyses, while others are used only for dynamic analyses. After developing lists of items and performance criteria/indicators, an "S" can be inserted in the matrices for items that are relevant only for static analyses for the potential application of the technology; "S/D" can be inserted for items that are relevant for both static and dynamic analyses; and "D" can be inserted for items that are relevant only for dynamic analyses. In many cases, only "S/D" and "D" will be used because the items that are relevant for static analyses are also generally relevant for dynamic analyses.

[Chemical Stabilization of Subgrades and Base Courses]: Task 10 Assessment Document

Inputs and Outputs for Design and Analysis Procedures, Matrix (Part 1)

	Specific Items for This Technology	Potential Applications											
		PAVEMENT FOUNDATION STAB.	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[1] OR STRUCTURES[2]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
PERFORMANCE CRITERIA/INDICATORS	Unconfined strength	S/D	S/D						S/D		S/D	S/D	S/D
	Resilient modulus on stabilized soil	S/D	S/D						S/D		S/D	S/D	S/D
	California Bearing Ratio	S/D	S/D						S/D		S/D	S/D	S/D
	R-value	S/D	S/D						S/D		S/D	S/D	S/D
	Durability	S/D	S/D						S/D		S/D	S/D	S/D
	Atterberg Limits	S/D	S/D						S/D		S/D	S/D	S/D
SUBSURFACE CONDITIONS	Atterberg Limits	S/D	S/D						S/D		S/D	S/D	S/D
	Sieve Analysis	S/D	S/D						S/D		S/D	S/D	S/D
	Water Content	S/D	S/D						S/D		S/D	S/D	S/D
	Swelling Potential	S/D	S/D						S/D		S/D	S/D	S/D
	Uniformity	S/D	S/D						S/D		S/D	S/D	S/D
	Groundwater Level	S/D	S/D						S/D		S/D	S/D	S/D
	Sulfate Content	S/D	S/D						S/D		S/D	S/D	S/D
	Organic Material Content	S/D	S/D						S/D		S/D	S/D	S/D
	permeability	S/D	S/D						S/D		S/D	S/D	S/D
	Soil classification	S/D	S/D						S/D		S/D	S/D	S/D
LOADING CONDITIONS	Traffic Load	S/D	S/D						S/D		S/D	S/D	S/D
	Construction Load	S/D	S/D						S/D		S/D	S/D	S/D

[1] Embankments are defined as soil or rock fill that may or may not be reinforced

[2] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

Inputs and Outputs for Analysis and Design Procedures, Matrix (Part 2)

		Potential Applications											
	Specific Items for This Technology	PAVEMENT FOUNDATION STABILIZATION	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[3] OR STRUCTURES[4]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
MATERIAL CHARACTERISTICS	Type of Stabilizer	S/D	S/D						S/D		S/D	S/D	S/D
	Percent of Stabilizer	S/D	S/D						S/D		S/D	S/D	S/D
	Strength (Compressive and Flexure)	S/D	S/D						S/D		S/D	S/D	S/D
	Durability	S/D	S/D						S/D		S/D	S/D	S/D
	Stiffness	S/D	S/D						S/D		S/D	S/D	S/D
	Swelling Potential	S/D	S/D						S/D		S/D	S/D	S/D
	pH Value	S/D	S/D						S/D		S/D	S/D	S/D
CONSTRUCTION TECHNIQUES	Mixed-In-Plant	S/D	S/D						S/D		S/D	S/D	S/D
	Central Plant	S/D	S/D						S/D		S/D	S/D	S/D
GEOMETRY	Depth of Stabilization	S/D	S/D						S/D		S/D	S/D	S/D
	Length and Area of Stabilization	S/D	S/D						S/D		S/D	S/D	S/D

[3] Embankments are defined as soil or rock fill that may or may not be reinforced
[4] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

DESIGN/ANALYSIS PROCEDURE ASSESSMENT, INSTRUCTIONS

A matrix has been developed to assess existing design/analysis procedures. The matrix contains four sections: Design/Analysis Procedures, References, Applications, and Assessment of Design/Analysis Procedure. Each of these sections is described below.

DESIGN/ANALYSIS PROCEDURES

Some design/analysis procedures have recognized names, such as the Coherent Gravity Method for MSE walls. For such cases, list the names of these procedures in this section of the matrix. If the procedure does not have a recognized name, provide a phrase that can be used to identify the procedure.

REFERENCES

Each reference addressing a design/analysis procedure should be listed in author (date) format in this portion of the matrix. If a given reference addresses a design/analysis procedure, insert a check in the appropriate box. Some references will address multiple design/analysis procedures and some design/analysis procedures will be addressed by multiple references. Complete citations for the references can be found in the technology's bibliography document.

APPLICATIONS

In some cases, the design/analysis of a particular technology may differ significantly from one application to another. This portion of the matrix is for recording the correspondence between design/analysis procedures and applications. If a given design/analysis procedure addresses a particular application, insert a check in the appropriate box.

ASSESSMENT OF DESIGN/ANALYSIS PROCEDURES

This section of the matrix is for assessing the existing design/analysis procedures using the categories described below. In general, H stands for high, M for medium, L for low, U for insufficient information to permit a rating, and N/A for not applicable. The U category should be used only if necessary. The N/A will seldom apply, but is included for completeness. Further discussion of these ratings is provided below.

Performance Criteria/Indicators *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

- H: The design procedure appropriately uses performance criteria, and/or the analysis procedure generates appropriate performance indicators.
- M: The design procedure uses appropriate performance criteria to a limited extent, and/or the analysis procedure generates appropriate performance indicators to a limited extent.
- L: The design procedure does not appropriately use performance criteria, and/or the analysis procedure does not generate appropriate performance indicators.
- U: References for this design/analysis procedure do not provide sufficient information to enable a rating.
- N: Performance criteria/indicators are not applicable to the design/analysis procedure.

<u>Subsurface Conditions</u> ***<u>(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)</u>***

- H: The design/analysis procedure appropriately uses relevant information about subsurface conditions.
- M: The design/analysis procedure uses relevant information about subsurface conditions to a limited extent.
- L: The design/analysis procedure does not adequately use relevant information about subsurface conditions.
- U: References for this design/analysis procedure do not provide sufficient information to enable a rating.
- N: Subsurface conditions are not applicable to the design/analysis procedure.

<u>Loading Conditions</u> ***<u>(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)</u>***

- H: The design/analysis procedure appropriately uses relevant information about loading conditions.
- M: The design/analysis procedure uses relevant information about loading conditions to a limited extent.
- L: The design/analysis procedure does not adequately use relevant information about loading conditions.
- U: References for this design/analysis procedure do not provide sufficient information to enable a rating.
- N: Loading conditions are not applicable to the design/analysis procedure.

<u>Material Characteristics</u> ***<u>(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)</u>***

- H: The design/analysis procedure appropriately uses relevant construction material characteristics.
- M: The design/analysis procedure uses relevant construction material characteristics to a limited extent.
- L: The design/analysis procedure does not adequately use relevant construction material characteristics.
- U: References for this design/analysis procedure do not provide sufficient information to enable a rating.
- N: Material characteristics are not applicable to the design/analysis procedure.

<u>Construction Techniques</u> ***<u>(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)</u>***

- H: The design/analysis procedure appropriately incorporates relevant considerations of construction technique.
- M: The design/analysis procedure incorporates relevant considerations of construction technique to a limited extent.
- L: The design/analysis procedure does not incorporate relevant considerations of construction technique.
- U: References for this design/analysis procedure do not provide sufficient information to enable a rating.
- N: Differences in construction techniques are not applicable to the design/analysis procedure.

Geometry *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

H: The design/analysis procedure produces the geometric information that should be included in the plans and specifications for construction.

M: The design/analysis procedure produces most of the geometric information that should be included in the plans and specifications for construction.

L: The design/analysis procedure does not produce sufficient geometric information for developing plans and specifications for construction.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Geometric outputs are not applicable to the design/analysis procedure.

Validation of Procedure

H: The design/analysis procedure has been validated to a great extent. Methods of validation may include instrumented case histories; the absence of known failures due to inadequacy of the design/analysis procedure; long-term performance data; extensive numerical; and/or physical modeling.

M: The design/analysis procedure has been validated with limited case histories and limited numerical and/or physical modeling.

L: The design/analysis procedure has not been validated, or there are failures due to inadequacy of the design/analysis procedure.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Rational-Empirical Basis

R: The design/analysis procedure is based primarily on rational principles of soil mechanics, mechanics of materials, and methods of analysis.

S: The design/analysis procedure is semi-mechanical and semi-empirical.

E: The design/analysis procedure is primarily empirical.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Ease of Use

H: The design/analysis procedure can be implemented by practicing engineers with tools readily available to them in an amount of time consistent with the degree of complexity and importance of the application (if intricate analyses are required, user-friendly software is available to perform these analyses). Procedure is highly standardized and can easily be applied to a variety of different site and loading conditions.

M: The design/analysis procedure can be implemented by practicing engineers, but implementation requires an excessive amount of time, it involves analysis methods not typically used in geotechnical practice, and/or the procedure cannot be easily applied to a variety of site and loading conditions.

L: The design/analysis procedure is complex and cannot be implemented by most practicing geotechnical engineers.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

LRFD Status

Y: The design/analysis procedure is an LRFD procedure.
N: The design/analysis procedure is not an LRFD procedure.
U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Mechanistic-Empirical Pavement Design Status (Element 3)

Y: The design/analysis procedure is a mechanistic-empirical pavement design procedure.
N: The design/analysis procedure is not a mechanistic-empirical pavement design procedure.
U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

DESIGN/ANALYSIS PROCEDURE ASSESSMENT MATRIX (PART 1)

REFERENCES[5]	Design/Analysis Procedure									
	Lime Stabilization	Cement Stabilization	Fly Ash Stabilization	Asphalt Stabilization	Combination Stabilization					
ACAA (2008)			✔							
Army and Air Force (1994)	✔	✔								
Adaska and Luhr (2004)		✔								
Austroads (1998)	✔	✔								
Christopher et al. (2006)		✔								
Eades et al. (1966)	✔									
Glogowshi et al. (1992)			✔							
Little (1995)	✔									
National Lime Association (2000)	✔									
PCA (1992)		✔								
Qubain et al. (2000)	✔									
Terrel et al. (1979)	✔	✔		✔	✔					
Thompson (1970)	✔									
TRB (1987)	✔	✔		✔						
Winterkorn and Pamukcu (1990)	✔	✔		✔						

[5] Complete citations for the references shown above can be found in the bibliography document for this technology.

DESIGN/ANALYSIS PROCEDURE ASSESSMENT MATRIX (PART 2)

		Design/Analysis Procedure									
		Lime Stabilization	Cement Stabilization	Fly Ash Stabilization	Asphalt Stabilization	Combination Stabilization					
APPLICATIONS	PAVEMENT FOUNDATION STABILIZATION	✔	✔	✔	✔	✔					
	CONSTRUCTION WORKING PLATFORMS	✔	✔	✔	✔	✔					
	COMPACTION										
	VOID FILLING										
	RECYCLING/REUSE										
	DRAINAGE										
	MOISTURE BARRIER/SEPARATION LAYER										
	SUPPORT OF EMBANKMENTS OR STRUCTURES	✔	✔	✔	✔	✔					
	LIQUEFACTION MITIGATION										
	SETTLEMENT REDUCTION	✔	✔	✔	✔	✔					
	THICKNESS REDUCTION OF PAVEMENT SECTION	✔	✔	✔	✔	✔					
	PROLONGING PAVEMENT SERVICE LIFE	✔	✔	✔	✔	✔					
ASSESSMENT	PERFORMANCE CRITERIA/INDICATORS	H	H	H	H	H					
	SUBSURFACE CONDITIONS	H	H	H	H	H					
	LOADING CONDITIONS	M	M	M	H	M					
	MATERIAL CHARACTERISTICS	H	H	H	H	H					
	CONSTRUCTION TECHNIQUES	L	H	H	H	H					
	GEOMETRY	M	M	M	M	M					
	VALIDATION OF PROCEDURE	H	H	H	H	H					
	RATIONAL-EMPIRICAL BASIS	S	S	S	S	S					
	EASE OF USE	H	H	H	H	H					
	LRFD STATUS										
	MECH. – EMP. PVMT. DESIGN STATUS	N	N	N	N	N					

DESIGN/ANALYSIS PROCEDURE ASSESSMENT COMMENTS

The following section can be used to provide a descriptive summary of the procedure and to comment on the ratings given in the Design Procedure Assessment Matrix. The ratings in this section should correspond to those given in the Matrix.

DESIGN/ANALYSIS PROCEDURE:	**Lime Stabilization**
REFERENCE(S):	**Army and Air Force (1994), Austroads (1998), Little (1995), Eades et al. (1966), National Lime Association (2000), Terrel et al. (1979), Thompson 1970, TRB (1987), Qubain et al. (2000), Winterkorn and Pamukcu (1990)**

Summary of Procedure: Determining lime content is the primary objective of mixture design for lime stabilization. The optimum lime content is dependent on how the stabilized material will be used and the soil constituents. The design objects may involve a reduction in plasticity, construction expediency, or permanent engineering changes which affect the strength/stiffness of the mixture and performance of the pavement which contains the treated layers. Mixture preparation, specimen preparation, curing conditions and testing are four factors considered as part of a laboratory testing program. Special testing is required for sulfate-bearing clay to prevent deleterious sulfate-induced heave. Table 1 shows the general stabilizing effect of lime on different soil types.

Table 1. General stabilizing effects of lime on different soils types (from Winterkon and Pamukcu 1990)

Type of Soil	Untreated					Lime Treated[a]				
	Triaxial	*CBR*	*R-Value*	*k-Value*	*Cohesiometer*	*Triaxial*	*CBR*	*R-Value*	*k-Value*	*Cohesiometer*
Heavy clay	5.5	2	20	100	—	3.2–3.5	15–30	55–69	250–350	350–850
Light clay	4.5	5	35	150	—	2.9–3.4	20–40	60–75	300–400	450–700
Sandy clay	3.7	12	50	200	—	2.4–3.0	35–60	65–80	400–500	550–850
Granular soil $PI = 8+$	3.2	30	65	250	—	1.5–2.7	50–75	70–80+	450+	650+
Clay gravel $PI = 6$ to 10	2.6	50	75	400	—	1.0–1.6	70–100+	80+	500+	800+

[a] Based on use of 4–6 percent lime for clay soils and 2–4 percent for granular and clay-gravel types. Triaxial and cohesiometer values are based on approximately 18 days of laboratory curing, CBR on 4 days curing (soaked), and *R*-value on about 2 days curing. The stability values of lime-treated specimens increase markedly with longer or accelerated curing: e.g., curing CBR specimens for 2 days at 120°F prior to soaking will nearly double the CBR values. This accelerated curing would correspond approximately to 30 to 45 days of summer field curing.

Because applications of lime can be broad in stabilization, several mix design methods have been developed. According to TRB (1987), these methods are:

1. California procedure (Terrel et al. 1979)
2. Eades and Grim procedure (Eades et al. 1966)
3. Illinois procedure (Terrel et al. 1979)
4. Oklahoma procedure (TRB 1987)
5. South Dakota procedure (TRB 1987)
6. Texas procedure (AASHTO T-220)
7. Thompson procedure (Thompson 1970)
8. Virginia procedure (VTM-11 Virginia Test Method for lime stabilization)

As an example, the Texas procedure is summarized below.
Step 1: Based on the grain size and PI data, the lime percentage is selected from Figure1.

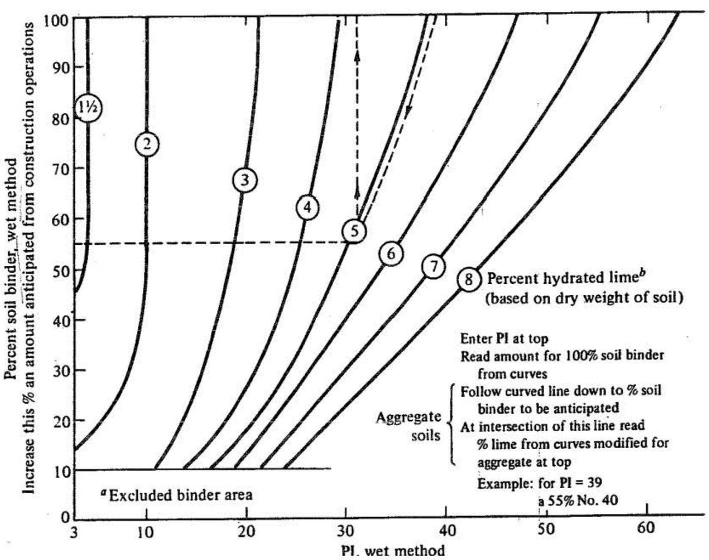

Figure 1. Recommended amounts of lime for stabilization of subgrades and bases (from Terrel et al. 1979)

Step 2: Optimum moisture and maximum dry density of the mixture are determined in accordance with AASHTO T-212 or Tex-113-E.

Step 3: Test specimens 6 in (15.2 cm) in diameter and 8 in. (20.3 cm) in height are compacted at optimum moisture content to maximum dry density.

Step 4: All specimens are placed in a triaxial cell and cured in the following manner:
a: Cool to room temperature .
b: Dry at temperature not exceeding 60° C (140° F) for about 6 hr until one-third of the molding moisture is remove.
c: Cool for at least 8 hr.
d: Subject specimens to water exposure via capillary action for 10 days (AASHTO T-212).

Step 5: The cured specimens are tested in unconfined compression with AASHTO T-212 section 7 and 8 or Tex-117-E.

The design process flow chart is shown in Figure 2. Two design criteria are used pavement structural behavior and durability requirement. In addition, swell needs to be reduced to a satisfaction level for lime-modified soil.
To deal with sulfate induced problems with lime stabilized soils, the National Lime Association (2000) provides guidelines as following:

> *Sulfate levels too low to be of concern:* The total level of soluble sulfates is below 0.3% (3000 ppm). The general construction procedure is followed, due to a low risk of harmful reaction.

Sulfate levels of moderate risk: The total levels of soluble sulfates are between 0.3% (3000 ppm) to 0.5% (5000 ppm). During construction, water content should be at least 3% to 5% above optimum for compaction. Mellowing period may be extended longer than 72 hours.

Sulfate levels of moderate to high risk: The total levels of soluble sulfates are between 0.5% (5000 ppm) to 0.8% (8000 ppm). The same mix design and construction can be followed as same as soil containing 0.3-0.5 % sulfate. Additionally, the laboratory test is recommended to determine swell potential before treatment, which also helps find the required period of mellowing between mixing and compaction.

Sulfate levels of high and unacceptable risk: The total levels of soluble sulfates are greater than 0.8% (8000 ppm). Due to high sulfate levels, treatment requires lime slurry, mixing, mellowing, curing water contents of 3%-5% above optimum for compaction, and mellowing period may be extended longer than 72 hours. The double application of lime may be applied too.

Although the benefits of improved soil properties are not considered into most current design approaches in United States, a study conducted by Qubain et al (2000) shows that lime treated subgrade soil can be successfully incorporated into pavement design with economic benefit by increasing the strength of subgrade. Three approaches were applied in this study: (1) utilizing an effective resilient modulus for the lime treated subgrade, (2) applying a very conservative CBR of 15 to account for lime stabilization, and (3) considering the lime-stabilized subgrade as subbase and assigning it a structural –layer coefficient. Little information is available in the literature, however, that documents the long term performance of stabilized soils for permanent foundation materials.

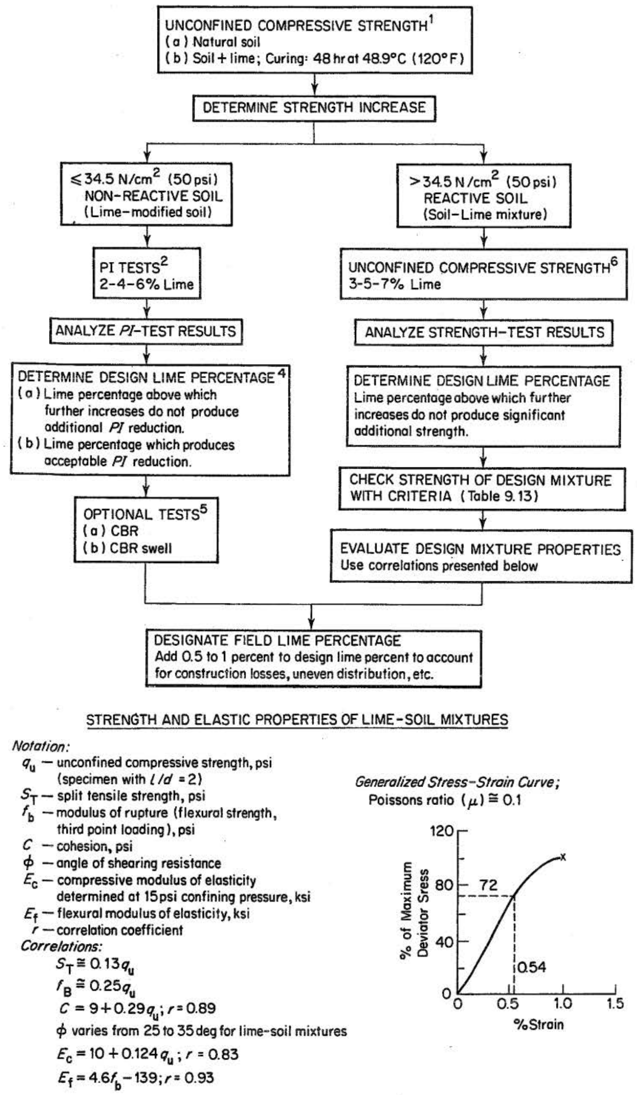

Figure 2. Mixture design for lime-treated soils according to Thompson procedure (from **Winterkorn and Pamukcu 1990**)

Performance Criteria/Indicators

Comments: The designer makes a trial design and analyzes to determine if the design meets the certain performance criteria. Life cycle cost analysis and constructability issues are taken consideration in the further evaluations.

Rating: H

Subsurface Conditions

Comments: Generally use sieve analysis and PI of soil to select the proper stabilizer and content.

Rating: H

Loading Conditions

Comments: Design methods are usually based on the type of loading (traffic or construction loading).

Rating: M

Material Characteristics

Comments: Characteristic of lime is important for proper design, and a long term quality of project. Most types of lime are suit for soil stabilization. Lime specifications have been prepared by many agencies and groups.

Rating: H

Construction Techniques

Comments: Not addressed with these laboratory design methods

Rating: L

Geometry

Comments: These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.

Rating: M

Validation of Procedure

Comments: The design methods are accepted in profession, and validated through case studies.

Rating: H

Rational-Empirical Basis

Comments: These methods are highly based on theory. The content of lime may slightly (1 to 1.5 percent) for the content designed in laboratory for the field condition.

Rating: S

Ease of Use

Comments: These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.

Rating: H

LRFD Status

Comments: Not Applicable

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: This section is only used for the laboratory mix design.

Rating: N

Loading Conditions

Comments: Design methods are usually based on the type of loading (traffic or construction loading).

Rating: M

Material Characteristics

Comments: Characteristic of lime is important for proper design, and a long term quality of project. Most types of lime are suit for soil stabilization. Lime specifications have been prepared by many agencies and groups.

Rating: H

Construction Techniques

Comments: Not addressed with these laboratory design methods

Rating: L

Geometry

Comments: These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.

Rating: M

Validation of Procedure

Comments: The design methods are accepted in profession, and validated through case studies.

Rating: H

Rational-Empirical Basis

Comments: These methods are highly based on theory. The content of lime may slightly (1 to 1.5 percent) for the content designed in laboratory for the field condition.

Rating: S

Ease of Use

Comments: These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.

Rating: H

LRFD Status

Comments: Not Applicable

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: This section is only used for the laboratory mix design.

Rating: N

DESIGN/ANALYSIS PROCEDURE:	**Cement Stabilization**
REFERENCE(S):	**Army and Air Force (1994), Adaska and Luhr (2004), Austroads (1998), Christopher et al. (2006), PCA (1992), Terrel et al. (1979), TRB (1987), Winterkorn and Pamukcu (1990)**

Summary of Procedure: Table 1 and Table 2 provide cement requirements for various subsurface soils in accordance with AASHTO and Unified soil classification systems. For the design of cement stabilized system, the general considerations are compressive strength, durability, and density. If mixed trial samples need meet specified durability requirement, a more detailed testing program is required for determination of the cement content. According to Christopher et al. (2006), the resistance to sulfate attack is different for cement treated fine-grained and coarse-grained soil. Granular soil-cements are not susceptible to sulfate attack. If fine-grained soil has more than 1% sulfate, cement treatment is not recommended.

Table 1. Typical cement requirement for various soil types (from Winterkon and Pamukcu 1990)

AASHTO Soil Classification	*Unified Soil Classification*	*Normal Range of Cement Requirements[b]*		*Typical Cement Content for Moisture–Density Test (ASTM D558), percent by weight*	*Typical Cement Contents for Wet–Dry (ASTM D559) and Freeze–Thaw Tests (ASTM D560), percent by weight*
		percent by vol.	*percent by wt.*		
A-1-a	GW, GP, GM, SW, SP, SM	5–7	3–5	5	3– 5– 7
A-1-b	GM, GP, SM, SP	7–9	5–8	6	4– 6– 8
A-2	GM, GC, SM, SC	7–10	5–9	7	5– 7– 9
A-3	SP	8–12	7–11	9	7– 9–11
A-4	CL, ML	8–12	7–12	10	8–10–12
A-5	ML, MH, CH	8–12	8–13	10	8–10–12
A-6	CL, CH	10–14	9–15	12	10–12–14
A-7	MH, CH	10–14	10–16	13	11–13–15

[a] PCA (1978).
[b] Does not include organic or poorly reacting soils. Also, additional cement may be required for severe exposure conditions such as slope protection.

Table 2. Average cement requirement for B and C horizon silty and clayey; and sandy soils (from Winterkon and Pamukcu 1990)

(i) Silty and Clayey Soils

AASHTO Group Index	Material Between 0.05 mm and 0.005 mm, Percent	Cement Content, Percent by Weight — Maximum Density, lb/ft³: 90–94	95–99	100–104	105–109	110–114	115–119	120 or More
0–3	0–19	12	11	10	8	8	7	7
	20–39	12	11	10	9	8	8	7
	40–59	13	12	11	9	9	8	8
	60 or more	—	—	—	—	—	—	—
4–7	0–19	13	12	11	9	8	7	7
	20–39	13	12	11	10	9	8	8
	40–59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
8–11	0–19	14	13	11	10	9	8	8
	20–39	15	14	11	10	9	9	9
	40–59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12–15	0–19	15	14	13	12	11	9	9
	20–39	16	15	13	12	11	10	10
	40–59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16–20	0–19	17	16	14	13	12	11	10
	20–39	18	17	15	14	13	11	11
	40–59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

(ii) Sandy Soils

Material Retained on No. 4 Sieve, Percent	Material Smaller than 0.05 mm, Percent	Cement Content, Percent by Weight — Maximum Density, lb/ft³: 105–109	110–114	115–119	120–124	125–129	130 or More
0–14	0–19	10	9	8	7	6	5
	20–39	9	8	7	7	5	5
	40–50	11	10	9	8	6	5
15–29	0–19	10	9	8	6	5	5
	20–39	9	8	7	6	6	5
	40–50	12	10	9	8	7	6
30–45	0–19	10	8	7	6	5	5
	20–39	11	9	8	7	6	5
	40–50	12	11	10	9	8	6

* PCA (1956).

The short-cut methods developed by the Portland Cement Association (PCA) are only applicable for sandy soil (PCA, 1992). There are two methods A and B. Method A is for soils not containing material retained on the No.4 sieve, and Method B is for soils containing material retained on the No.4 sieve. The design procedure of Method B is summarized blow.

Step 1. Perform a sieve analysis and determine bulk specific gravity of soil.

Step 2. Conduct a moisture-density test to determine the maximum density and optimum moisture content for a mixture of the soil and Portland cement, according to ASTM D 558-57 and AASHTO T 134-57 (Methods of Test for Moisture-Density Relations of Soil-Cement Mixture). Figure 5 can be used to determine an estimated maximum density of the soil and cement mixture being tested. The estimated maximum density, the percentage of material, smaller than 0.05 mm, and the percentage of material retained on the No. 4 sieve can be used with Figure 6 to determine the cement content by weight to use in the test.

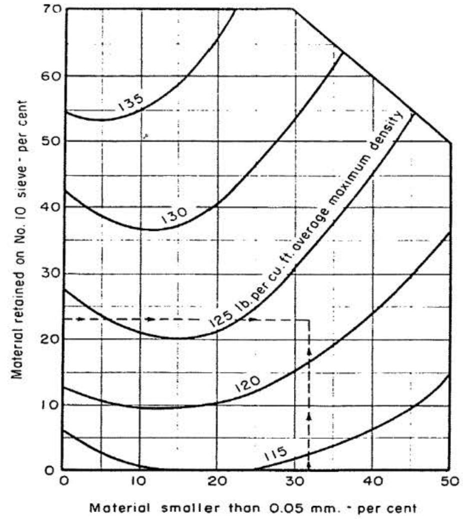

Figure 3 Average maximum densities of soil-cement mixtures containing material retained on the No.4 sieve (from Winterkon and Pamukcu 1990)

Step 3. Use the maximum density obtained by test in step 2 to determine from Figure 4 the indicated cement requirement.

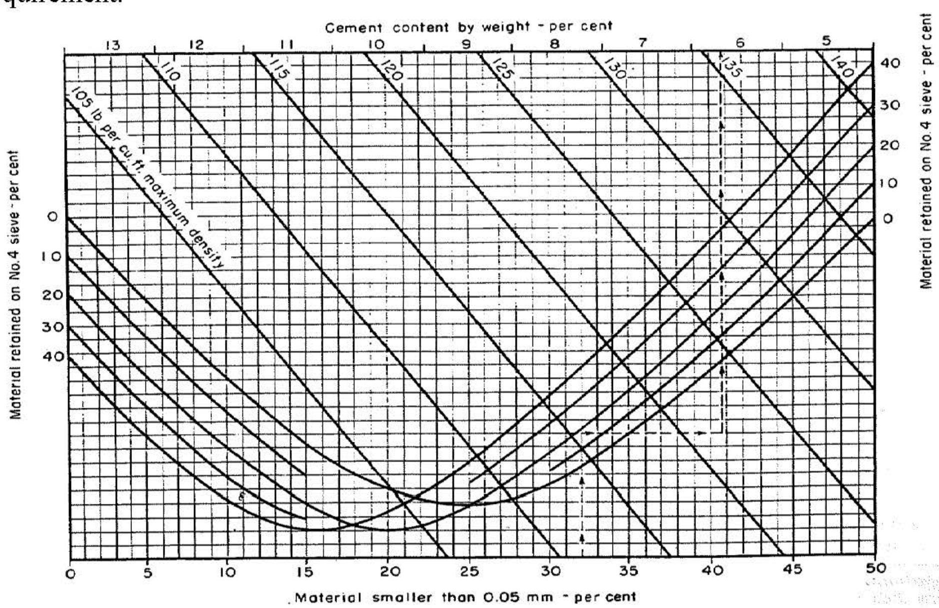

Figure 4. Indicated cement contents of soil-cement mixtures containing material retained on the No.4 sieve (from Winterkon and Pamukcu 1990)

Step 4. Use total material as described in step 2 and the indicated cement factor obtained in step 3 to mold compressive-strength test specimens in triplicate at maximum density and optimum moisture content.

Step 5. Determine the average compressive strength of the specimens after 7 days moist-curing.

Step 6. Determine from Figure 5 the minimum allowable compressive strength for the soil-cement mixture. If the average compressive strength obtained in step 5 equals or exceeds the minimum allowable strength, the indicated cement factor by weight obtained in step 3 is adequate. Reflective cracks occurred in flexible pavements may cause poor performance problems. Several approaches to control reflective cracking from the cement treated pavement bases are discussed in Adaska and Luhr (2004).

- Increasing the density and reducing the moisture content during compaction.
- Using a pre-cracking technique. For instance, several passes of a vibratory roller over the cement stabilized bases are preformed one day to two days after compaction. That will generate hundreds of tiny micro cracks, so single transverse cracks are prevented.
- Placing a chip-seal, geotextile or granular layer between the asphalt surface and the stabilized base. Then the stress concentrations resulted from cracks in the cement treated base are relieved. The potential of reflective cracking is eliminate.

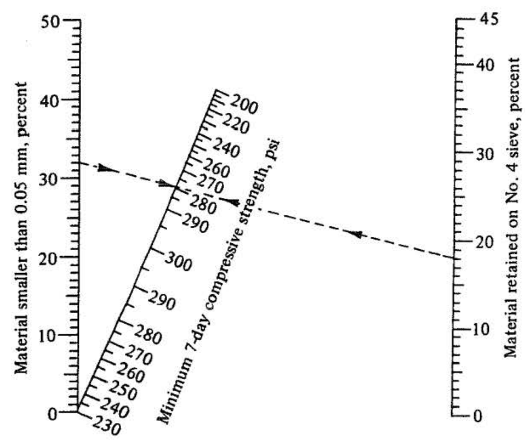

Figure 5. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No.4 sieve (from Winterkon and Pamukcu 1990)

Performance Criteria/Indicators

Comments: *Time and cost help to determine the stabilization method. The strength and durability of the mixed soil are usually evaluated.*

Rating: *H*

Subsurface Conditions

Comments: *Cement stabilization design method is heavily relied on the subsurface conditions, such as plasticity index and PI.*

Rating: *H*

Loading Conditions

Comments: *Design methods are usually based on the type of loading (traffic or construction loading).*

Rating: *M*

Material Characteristics

Comments: Several different cement types are successfully applied for cement stabilization of soil. So far Type II cement has largely replaced the Type I cement, which has greater sulfate resistance while the cost is often the same.

Rating: H

Construction Techniques

Comments: Pulverization and uniform mixing of are best accomplished in central mixing plants. However, central mixing plants may be limited for small projects due to cost.

Rating: H

Geometry

Comments: These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.

Rating: M

Validation of Procedure

Comments: The design methods are accepted in profession, and validated through case studies.

Rating: H

Rational-Empirical Basis

Comments: These methods are highly based on theory. The content of cement may increase slightly for the content designed in laboratory for the field condition.

Rating: S

Ease of Use

Comments: These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.

Rating: H

LRFD Status

Comments: Not Applicable

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: This section is only used for the laboratory mix design.

Rating: N

DESIGN/ANALYSIS PROCEDURE:	**Fly Ash Stabilization**
REFERENCE(S):	**ACAA (2008), Glogowski (1992)**

Summary of Procedure: Class C fly ash is recommended to stabilize fine-grained plastic soils such as clay, as well as coarse-grained soil (ACAA 2008). Some factors are important when develops the mix design procedure for stabilization applications utilizing self-cementing ash. Based on ACAA (2008), firstly self-cementing ash hydrates at a much more rapid rate than Portland cement, and 2-hour delay in compaction can result in a decrease in maximum density of up to 1.6 KN/m^3 (10 pcf) or more. Secondly, moisture content influences the compressive strength. To deal sulfate attack problems for stabilized materials, fly ash with the high sulfate concentrations should be avoided.

A laboratory study by Ferguson (1993) recommended that a fly ash content was 16 % for mixing with subgrade materials to obtain maximum California Bearing Ratio. No standard test procedures currently exist for the design of material stabilized with self-cementing ash (ACAA, 2008). However, an effective procedure can be used to determine moisture-density and moisture-strength relationships of the stabilized material, based on adaptation of ASTM C593 (Fly Ash and Other Pozzolans for Use with Lime) and ASTM D 1633 (Compressive Strength of Molded Soil-Cement Cylinders). The design procedure follows:

Step 1. Blend soil, fly ash and water to make a minimum of five test specimens. Moisture contents of the specimen should be up to 10% below to 6% above the optimum moisture content for maximum density. The specimens have a height-to-diameter ratio of 1.15.

Step 2. Compact specimens over a wide range of moisture contents. Use specified compaction time delay (<2 hours) and 102-mm (4.0-inch)-diameter by 117-mm (4.625-inch)-high mold. Standard Proctor compactive energy or modified proctor compactive energy may be used.

Step 3.Cure test specimens for a period of 7 days at 38°C (100°F) in accordance with ASTM C593.

Step 4. Determine compressive strength of specimens.

Modification of the compaction procedures may be required for mix designs of granular materials stabilized with ash. For stabilized pavement section or other applications where a higher degree of stabilized is desired, additional laboratory tests needs to conducted assess properties of the stabilized materials required for specific design procedures. Stabilized granular material to be used for pavement base course or subbase tests can be evaluated through ASTM C593 to assess the freeze-thaw durability of the stabilized materials.

Performance Criteria/Indicators

Comments: *Time and cost help to determine the stabilization method. The strength and durability of the mixed soil are usually evaluated.*

Rating: *H*

Subsurface Conditions

Comments: *Fly ash stabilization design method is heavily relied on the subsurface conditions, such as data from plasticity index and Atterberg limit.*

Rating: H

Loading Conditions

Comments: Design methods are usually based on the type of loading (traffic or construction loading).

Rating: M

Material Characteristics

Comments: It needs to identify the source or sources of fly ash to be used. A minimum calcium oxide percent may be specified. Fly ash with high calcium oxide of 20 percent or higher is good for soil stabilization without the use of additional lime.

Rating: H

Construction Techniques

Comments: Compaction should be completed within two hours after the soil is mixed, because soil stabilized with Class C fly ash can begin set quickly. The construction may need a retarder to prevent quick set of fly ash if immediate compaction is not allowed.

Rating: H

Geometry

Comments: These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.

Rating: M

Validation of Procedure

Comments: The design methods are accepted in profession, and validated through case studies.

Rating: H

Rational-Empirical Basis

Comments: These methods are highly based on theory. Based on the field experience, the content of the stabilizer may increase slightly for the content designed in laboratory.

Rating: S

Ease of Use

Comments: These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.

Rating: H

LRFD Status

Comments: Not Applicable

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: This section is only used for the laboratory mix design.

Rating: N

DESIGN/ANALYSIS PROCEDURE:	**Asphalt Stabilization**
REFERENCE(S):	**Army and Air Force (1994), Terrel et al. (1979), Winterkorn and Pamukcu (1990)**

Summary of Procedure: According to Army and Air Force (1994), the following equation can be used to estimate the preliminary quantity of cutback asphalt for subgrade stabilization.

$$P = \frac{0.02(a)+0.07(b)+0.15(c)+0.20(d)}{(100-S)} \times 100$$

P = percent cutback asphalt by weight of dry aggregate
a= percent of mineral aggregate retained on No. 50 sieve
b= percent of mineral aggregate passing No.50 sieve and retained on No. 100 sieve
c= percent of mineral aggregate passing No. 100 and retained on No. 200 sieve
d=percent of mineral aggregate passing No.200
S= percent solvent

Table 3 in Army and Air Force (1994) provides the preliminary quantity of emulsified asphalt for subgrade stabilization.

Table 3. Emulsified asphalt requirements (from Army and Air Force 1994)

	Pounds of Emulsified Asphalt per 100 pound of Dry Soil at Percent Passing No.10 Sieve					
Percent Passing No. 200 Sieve	<50	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.4
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.1
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.1
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.4
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

The final content of cutback or emulsified asphalt needs be ensured using the results of the Marshal Stability Test. A bituminous-stabilized soil may not show increased stability with designed amounts of bituminous. If this problem occurs, two approaches are used to solve the problem including that (1) the gradation of the soil should be modified, (2) another type of bituminous material should be used.

Performance Criteria/Indicators

Comments: Time and cost help to determine the stabilization method. The strength and durability of the mixed soil are usually evaluated.

Rating: H

Subsurface Conditions

Comments: The design method is heavily relied on the subsurface conditions, such as data from plasticity index and Atterberg limit.

Rating: H

Loading Conditions

Comments: Design methods are usually based on the type of loading (traffic or construction loading).

Rating: H

Material Characteristics

Comments: The higher carbon content in fly ash tends to inhibit the pozzolanic reactivity of a fly ash. The carbon content of the fly ash is limited to 12 percent, if the adequate strength is achieved.

Rating: H

Construction Techniques

Comments: The type of the asphalt is dependent on the method of construction and the equipment available. The mixing technologies involve mixed-in -place and central plant (both hot and cold operations). In general, asphalt cements are limited to hot central plant mixing operations.

Rating: H

Geometry

Comments: These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.

Rating: M

Validation of Procedure

Comments: The design methods are accepted in profession, and validated through case studies.

Rating: H

Rational-Empirical Basis

Comments: These methods are highly based on theory. Based on the field experience, the content of cement may increase a slightly for the content designed in laboratory for the field condition.

Rating: S

Ease of Use

Comments: These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.

Rating: H

LRFD Status

Comments: Not Applicable

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: This section is only used for the laboratory mix design.

Rating: N

DESIGN/ANALYSIS PROCEDURE:	**Combination Stabilizer**
REFERENCE(S):	**Terrel et al. (1979)**

Summary of Procedure: Using combination stabilizer materials is dependent on the soil type and stabilizer constituents. Figure 6 presents a guideline for generally selecting the type and combination of stabilizers. Typically, a combination of stabilizers is recommended if soils have more than 25% passing No. 200 sieve and Plasticity Index more than 10. The first stabilizer pretreats the soil to alter its properties before treating it with the dominant (second) stabilizer. The quantity of the second stabilizer applied would be more than the first one.

According to Winterbon and Pamukcu (1990), lime content varies between 2 to 8 percent, and fly ash percent is in a range of 8 to 36 percent for lime-fly-ash and soil mixtures. The design ratio of lime to fly ash can be varied from 1:3 to 1:4 for reasons of economy and quality. For cement-fly ash and soil mixtures, the ratio of cement to fly ash varies between 3:7 and 1.5:8.5 for sandy soil. Typically cement to fly ash ratio is about 1:3 or 1:4.Table 4 shows the strength and durability criteria for lime-fly-ash and soil mixtures.

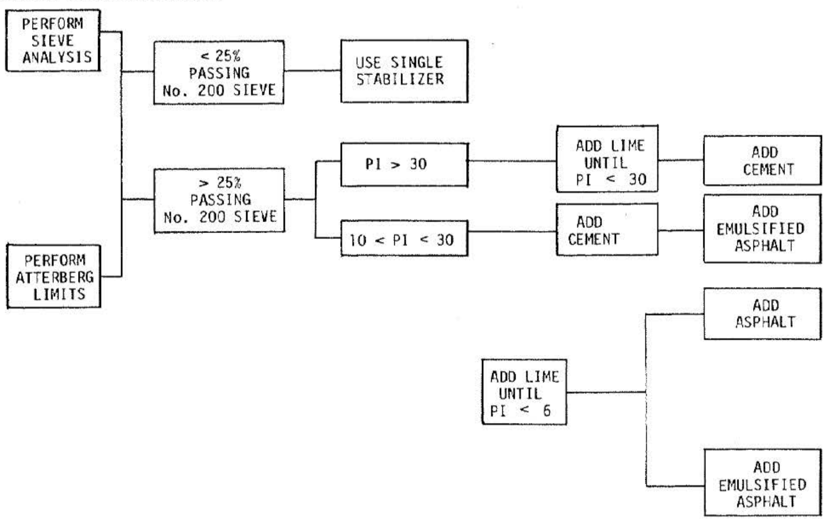

Figure 6. Selection of combination stabilizers (from Terrel et al. 1979)

Table 4.Strength and durability criteria for LFA-Soil mixtures (from Terrel et al. 1979)

Agency	*Test*	*Criteria*
	(a) Strength	
ASTM	ASTM C 593 Unconfined compression test 7-day cure at 100°F (38°C)	Min. 400 psi (2760 kPa)
British Road Research Laboratory	Unconfined compression test 28-day cure	Min. 25 psi (1720 kPa), except 400–500 psi (2760–3450 kPa) for clay soils and severe climatic conditions
	California Bearing Ratio	80% immediately beneath surface, and decreasing with depth
	(b) Durability[b]	
ASTM	ASTM C 593 Vacuum saturation method[c]	Min. 400 psi (2760 kPa)
Portland Cement Association	AASHTO T 135-70 and T136-70 wet–dry and freeze–thaw brushing tests	7–14% allowable weight loss, exact value dependent upon soil grain size
British Road Research Laboratory	Durability ratio (ratio of weathered strength to unweathered strength)	Min. 80%
	Iowa freeze–thaw test; index of resistance (ratio of weathered strength to unweathered strength)	Min. 80%

[a] After Meyers et al. (1976).
[b] Applicable in regions where climatic conditions are a factor in pavement performance.
[c] Approved revision; replaces freeze–thaw brushing test.

Performance Criteria/Indicators

Comments: *Time and cost help to determine the stabilization method. The strength and durability of the mixed soil are usually evaluated.*

Rating: *H*

Subsurface Conditions

Comments: *The design method is heavily relied on the subsurface conditions, such as data from plasticity index and Atterberg limit.*

Rating: *H*

Loading Conditions

Comments: *Design methods are usually based on the type of loading (traffic or construction loading).*

Rating: *M*

Material Characteristics

Comments: *The quality of stabilizers is essential to achieve the satisfactory results.*

Rating: *H*

Construction Techniques

Comments: *Heavy vehicles are not allowed on the lime-cement, and lime-emulsified asphalt or cement-emulsified stabilized soil prior to 7-to-10 day curing period.*

Rating: *H*

Geometry

Comments: *These methods are usually for shallow stabilization (pavement bases or subgrades). Stabilization depth is limited by the equipment for pulverization.*

Rating: *M*

Validation of Procedure

Comments: *The design methods are accepted in profession, and validated through case studies.*

Rating: *H*

Rational-Empirical Basis

Comments: *These methods are highly based on theory. The content of the stabilizer may increase slightly for the content designed in laboratory for the field condition.*

Rating: *S*

Ease of Use

Comments: *These methods are well designed for steps. They are easy to use. Figures and diagrams are provided and can be easy followed.*

Rating: *H*

LRFD Status

Comments: *Not Applicable*

Rating:

Mechanistic-Empirical Pavement Design Status

Comments: *This section is only used for the laboratory mix design.*

Rating: *N*

[Chemical Stabilization of Subgrades and Base Courses]: Task 10 Assessment Document
Design/Analysis Procedure Characterization Matrix

After completing the Design/Analysis Procedure Assessment, each of the technology's applications should be characterized based on the assessments of the relevant design procedures for that application. Several design/analysis procedures may exist for an application, but the intent here is to characterize the overall status of that application of the technology based on the previous assessments of all the relevant design/analysis procedures for that application. If desired, the next section can be used to comment on the characterizations.

	Potential Applications											
Design/Analysis Procedure Characterization Categories	PAVEMENT FOUNDATION STAB.	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[6] OR STRUCTURES[7]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
One preferred procedure exists: One of the existing design/analysis procedures is satisfactory and clearly preferred. No further development is needed.											✓	
Selection guidance: More than one design/analysis procedure and/or computer program exists for this application of the technology. Guidance is needed to select which procedure and/or computer program should be used. Selection of the most appropriate procedures may depend on project-specific parameters.	✓	✓										✓
Combine: More than one suitable design/analysis procedure exists. Procedures may need to be combined into a single consistent recommended procedure using the best elements of two or more procedures.												✓
Verification: An existing design/analysis procedure appears to be suitable; however, the accuracy and reliability of the procedure needs to be verified.												
Improve: An existing design/analysis procedure has suitable components, but improvement is needed in some areas.												
Transition: An existing design/analysis procedure needs to be transitioned into LRFD or mechanistic-empirical design format.												
Develop: No suitable design/analysis procedure exists, and a new design procedure must be developed								✓		✓		

[6] Embankments are defined as soil or rock fill that may or may not be reinforced
[7] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

Design/Analysis Procedure Characterization Comments

The following section can be used to comment on the characterizations given in the Design/Analysis Procedure Characterization Matrix. The characterizations in this section should correspond to those given in the Design/Analysis Procedure Characterization Matrix.

Pavement Foundation Stabilization

Comments: Has multiple documents with viable design method for different stabilization methods.

Characterization: Selection guidance

Construction Working Platforms

Comments: Has multiple documents with viable design method for different stabilization methods.

Characterization: Selection guidance

Compaction

Comments:

Characterization:

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: Develop

Liquefaction Mitigation

Comments:

Characterization:

Settlement Reduction

Comments:

Characterization: Develop

Thickness Reduction of Pavement Section

Comments: Includes mechanistic-empirical pavement design.

Characterization: One preferred procedure exists

Prolonging Pavement Service Life

Comments: Has multiple documents with viable design method for different stabilization methods.

Characterization: Selection guidance and combine

QC/QA OBJECTIVES

Construction quality is achieved by meeting established requirements, as detailed in project plans and specifications, including applicable codes and standards. Quality Control (QC) and Quality Assurance (QA) are terms applied to the procedures, measurements, and observations used to ensure that construction projects satisfy the requirements in the project plans and specifications. QC and QA are often misunderstood and used interchangeably. Herein, Quality Control refers to procedures, measurements, and observations used by the contractor to monitor and control the construction quality such that all applicable requirements are satisfied. Quality Assurance refers to measurements and observations by the owner or the owner's engineer to provide assurance to the owner that the facility has been constructed in accordance with the plans and specifications.

In order to assess the QC/QA methods for a technology, the assessor(s) should first develop a list of objectives for QC/QA activities. It is recommended that assessor(s) review the list of input and output items from the first matrix in this document as part of developing the list of QC/QA objectives. The general principal is that all the desired outputs from design procedures (many of which may also be inputs for analysis procedures) should be subject to QC/QA activities and should be reflected in the QC/QA objectives.

QC/QA Objectives
Spread Rate
Percent of Additive
Stability of Compacted Material
Pulverization and Scarification
Uniformity of Mixing
Mixing Efficiency
Density
Mixing Adequacy and Depth
Moisture Content

QC/QA Method Assessment, Instructions

A matrix has been developed to assess existing QC/QA methods. Six sections are contained in the matrix: QC/QA Methods, References, QC/QA Objectives, Applicability to QC and QA, Assessment of QC/QA Methods, and Usefulness of QC/QA Method for Application. Each of these sections is described below.

QC/QA Methods

In this portion of the matrix, list each QC/QA method that applies to the technology.

References

This section of the matrix should contain references in author (date) format that discuss QC/QA methods for the technology. For a given reference, insert a check in the appropriate box for each QC/QA method it addresses. Some references will address multiple QC/QA methods and some QC/QA methods will be addressed by multiple references.

QC/QA Objectives

This section of the matrix should contain the objectives listed in the QC/QA Objectives section of this document. If a QC/QA method helps achieve a particular objective, insert a check in the appropriate box.

Applicability to QC and QA

Some methods apply only to QC, some apply only to QA, and others apply to both QC and QA. In this portion of the matrix, insert a check in the appropriate box(es) if the method applies to QC, QA, or both QC and QA.

Assessment of QC/QA Method

This section of the matrix is used to assess the existing design methods using the categories described below. In general, H stands for high, M for medium, and L for low. Further discussion of these ratings is provided below to help the assessment.

Accuracy and Precision

H: The QC/QA method accurately and precisely assesses construction quality for this technology.

M: The QC/QA method provides an approximate assessment of construction quality for this technology.

L: The QC/QA method does not provide a reliable assessment of construction quality for this technology.

Adequacy of Coverage

H: The QC/QA method can be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil, using a reasonable number of tests.

M: The QC/QA method can be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil, but the number of tests required is significantly more than desirable.

L: The published QC/QA methods cannot be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil without an excessive number of tests.

Implementation Requirements

H: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are not excessive.

M: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are somewhat greater than desired.

L: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are prohibitive.

Applicability to Method Approach Specifications

H: The QC/QA method is applicable to method approach[8] specifications; example specifications incorporating the QC/QA method exist in the literature.

M: The QC/QA method is somewhat applicable to method approach specifications.

L: The QC/QA method is not applicable to method approach specifications.

Applicability to Performance Approach Specifications

H: The QC/QA method is applicable to performance approach [9] specifications; example specifications incorporating the QC/QA method exist in the literature.

M: The QC/QA method is somewhat applicable to performance approach specifications.

L: The QC/QA method is not applicable to performance approach specifications.

USEFULNESS OF QC/QA METHOD FOR APPLICATION

This portion of the matrix is for the assessor(s) to provide an overall rating of the usefulness of each QC/QA method for various applications. Each QC/QA method should be given an H, M, or L rating unless the method is not relevant to the application, in which case, an N should be inserted. The four ratings are described below.

H: The QC/QA method is highly useful for the application.

M: The QC/QA method somewhat useful for the application.

L: The QC/QA method is of little use for the application.

N: The QC/QA method is not relevant to the application.

[8]Method approach specifications require the contractor to produce and place a product using specified materials in definite proportions and with specific types of equipment and methods. The agency is responsible for performance provided that the contractor has followed the specified methods. (After http://www.fhwa.dot.gov/construction/specs.cfm and TRB Circular E-C074)

[9]Performance approach specifications encompass: End-Result specs; Quality Assurance specs; Performance-Related specs; Performance-Based specs; Warranty Provisions; and Incentive Provisions for Time and Quality (SHRP2 R07 Performance Specifications for Rapid Renewal project, 2009 TRB presentation). End-result specifications require the contractor to take the entire responsibility for producing and placing materials to achieve a specified final product. The agency's responsibility is to either accept or reject the final product or to apply a price adjustment commensurate with the degree of compliance with the specifications. (After http://www.fhwa.dot.gov/construction/specs.cfm and TRB Circular E-C074). End-result specifications are the typical type of performance approach specification used for Element 1 and 2 technologies.

QC/QA Method Assessment Matrix (Part 1)

		QC/QA Method[10]									
		Phenolphthalein Test	Soil Sampling	Spot or Overall Check	Chemical analysis	Nuclear gauge method	Visual Inspection	Dynamic Plate Load Test	Dynamic Cone Penetrometer Test	Static Plate Load Test	
References[11]	Army and Air Force (1994)	✓		✓			✓				
	Austroads (1998)			✓	✓	✓					
	Avalle and Grounds (2004)									✓	
	Landpac (2008)									✓	
	Little (1995)	✓		✓		✓					
	Qubain et al. (2006)	✓			✓	✓		✓	✓		
	PCA (1980)			✓		✓	✓				
	TRB (1987)	✓		✓		✓					
	Vennapusa and White (2009)							✓			
	White et al. (2005)					✓		✓			
QC/QA Objectives[12]	Application Rate			✓							
	Percent of Additive	✓			✓		✓				
	Stability of Compacted Material		✓					✓	✓	✓	
	Pulverization and Scarification		✓			✓					
	Uniformity of Mixing	✓					✓				
	Mixing Efficiency	✓	✓		✓		✓			✓	
	Density					✓					
	Mixing Adequacy and Depth	✓					✓				
	Moisture Content					✓	✓				

[10] These QC/QA Methods should match those shown in Part 2 of this matrix.
[11] Complete citations for the references shown above can be found in the bibliography document for this technology.
[12] These objectives should match those listed in the QC/QA Objectives section.

QC/QA Method Assessment Matrix (Part 2)

	QC/QA Method[13]									
	Phenolphthalein Test	Soil Sampling	Spot or Overall Check	Chemical analysis	Nuclear gauge method	Visual Inspection	Dynamic Plate Load Test	Dynamic Cone Penetrometer Test	Static Plate Load Test	
APPLICABLE TO QC	✔	✔	✔	✔	✔	✔	✔	✔	✔	
APPLICABLE TO QA	✔	✔			✔	✔	✔	✔	✔	
ACCURACY AND PRECISION	M	L to H	L to M	M	M to H	L to M	M to H	M	M to H	
ADEQUACY OF COVERAGE	M	L	L to M	M	L	M	M	M	L	
IMPLEMENTATION REQUIREMENTS	H	M	H	M	M	M	M	M	M	
APPLICABILITY TO METHOD APPROACH SPECS.	L	L	L	M	L	L	L	L	L	
APPLICABILITY TO PERFORMANCE APPROACH SPECS.	M	H	H	M	L to M	M	M	H	M	
PAVEMENT FOUNDATION STABILIZATION	M	H	M	M	H	M	H	H	H	
CONSTRUCTION WORKING PLATFORMS	M	H	M	M	H	M	H	H	H	
COMPACTION	N	N	N	N	N	N	N	N	N	
VOID FILLING	N	N	N	N	N	N	N	N	N	
RECYCLING/REUSE	N	N	N	N	N	N	N	N	N	
DRAINAGE	N	N	N	N	N	N	N	N	N	
MOISTURE BARRIER/ SEPARATION LAYER	N	N	N	N	N	N	N	N	N	
SUPPORT OF EMBANKMENTS OR STRUCTURES	M	H	M	M	M	M	H	H	H	
LIQUEFACTION MITIGATION	N	N	N	N	N	N	N	N	N	
SETTLEMENT REDUCTION	M	H	M	M	M	M	H	L	H	
THICKNESS REDUCTION OF PAVEMENT SECTION	L	H	L	M	L	L	H	H	H	
PROLONGING PAVEMENT SERVICE LIFE	M	H	M	M	H	M	H	H	H	

[13] These QC/QA Methods should match those shown in Part 1 of this matrix.

QC/QA METHOD ASSESSMENT COMMENTS

This section can be used to provide a descriptive summary of the method and to comment on the assessment and usefulness ratings given in the QC/QA Method Assessment Matrix. The General Comments paragraph under the heading below for Usefulness of QC/QA Method for Application is for comments that are relevant to all applications of the technology. Information about a QC/QA method that is unique to a particular application can be provided in the location indicated for that application. The ratings in this section should correspond to those given in the QC/QA Method Assessment Matrix. If available, numerical values (e.g., costs, coverage volume per tests) can be provided in the comments.

QC/QA METHOD:	**Phenolphthalein Test**
REFERENCE(S):	**Army and Air Force (1994), Austroads (1998), Qubain et al. (2006), TRB (1987)**

Method Summary: Phenolphthalein is a color-sensitive indicator and sprayed on soil to determine the presence of lime or cement in the field or laboratory (Army and Air Force 1994). A reddishpink color will develop when pH is equal to or greater than 10, which indicates a stabilizer is presented. Hence, the presence of the stabilizer and uniformity of the mixing can be checked.

Assessment of QC/QA Method

Accuracy and Precision

Comments: This method cannot precisely estimate the stabilizer content for depth of treatment, and only provides the visual verification of the stabilizer presence and mixing uniformity.

Rating: M

Adequacy of Coverage

Comments: It is only used for checking soil locally.

Rating: M

Implementation Requirements

Comments: Visualizing a reddishpink color in soil is a straight forward process requiring minimal training or experience.

Rating: H

Applicability to Method Approach Specifications

Comments: This method is not applicable for method specification.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: The quality of project can be accessed by this method.

Rating: M

Usefulness of QC/QA Method for Application

General Comments Phenolphthalein indicator solution is a good indicator to distinguish between areas that have been properly treated and untreated area. It also helps aid in indentifying areas where density test samples should be taken.

Pavement Foundation Stabilization

Comments:

Rating: *M*

Construction Working Platforms

Comments:

Rating: *M*

Compaction

Comments:

Rating: *N*

Void Filling

Comments:

Rating: *N*

Recycling/Reuse

Comments:

Rating: *N*

Drainage

Comments:

Rating: *N*

Moisture Barrier/Separation Layer

Comments:

Rating: *N*

Support of Embankments or Structures

Comments:

Rating: *M*

Liquefaction Mitigation

Comments:

Rating: *N*

Settlement Reduction

Comments:

Rating: *M*

Thickness Reduction of Pavement Section

Comments:

Rating: *L*

Prolonging of Pavement Service Life

Comments:

Rating: *M*

QC/QA METHOD:	Soil Sampling
REFERENCE(S):	

Method Summary: Soil sampling from fields can be helpful to conduct classification, strength, and modulus testing. It must be noted that strength and modulus testing conducted on laboratory compacted samples may result in different properties than field samples due to differences in stress conditions and soil structure. The following table provides a list of tests that can be performed on soil samples and its use for QC/QA.

Table 3. Summary of laboratory tests and its applicability for QC/QA

Test	QC or QA
Atterberg Limits	QC/QA
Water Content	QC/QA
Particle size distribution	QC/QA
Proctor	QC/QA
Density	QC/QA
Organic content	QC
Consolidation	QA
Shear Strength	QA
Resilient Modulus	QA
California Bearing Ratio	QA

Assessment of QC/QA Method

Accuracy and Precision

Comments: Accuracy and precision of the test depends on the test method. Most of these test methods are widely used in geotechnical engineering practice and have been standardized by ASTM and AASHTO.

Rating: L-H

Adequacy of Coverage

Comments: These tests represent soil properties of the sample obtained only. Experience is required to interpret soil layering information from multiple soil borings and samples.

Rating: L

Implementation Requirements

Comments: Disturbed samples from shallow depths can be obtained using hammer-driven Shelby tubes or test pit excavation.

Rating: H

Applicability to Method Approach Specifications

Comments: These tests are not usually incorporated in method based specifications. However, some of the tests may be used periodically during construction to assure that the methods are achieving the necessary ground improvement.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: If "undisturbed" soil samples are obtained, they provide a direct measurement of many soil properties and therefore can be used in performance approach specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments Obtaining samples enables visual inspection of the material and provides material for conducting a variety of QA related tests as described above. It is helpful to assess the improvement if before and after compaction are performed. Sampling applicability to each of the potential application is rated below.

Pavement Foundation Stabilization

Comments: The quality of the mixing can ensure the performance of pavement foundation.

Rating: H

Construction Working Platforms

Comments: The quality of the mixing can ensure the performance of construction working platforms.

Rating: H

Compaction

Comments:

Rating: N

Void Filling

Comments:

Rating: N

Recycling/Reuse

Comments:

Rating: N

Drainage

Comments:

Rating: N

Moisture Barrier/Separation Layer

Comments:

Rating: N

Support of Embankments or Structures

Comments:

Characterization: H

Liquefaction Mitigation

Comments:

Rating: N

Settlement Reduction

Comments:

Characterization: *H*

Thickness Reduction of Pavement Section

Comments: *The design thickness of a base or subbase course can be reduced if the stabilized material meets the specified gradation.*

Rating: *H*

Prolonging of Pavement Service Life

Comments: *The quality of the mixing can ensure the long term performance of pavement.*

Rating: *H*

QC/QA METHOD:	**Spot or Overall Check**
REFERENCE(S):	**Austroads (1998), Army and Air Force (1994), Little (1995), PCA (1980), TRB (1987)**

Method Summary: The spot and overall check method can be used for checking of the stabilizer application rate. Placing a tray or a mat of known area on the surface and weighing the quantity of stabilizing agent deposited on it after spreading can be used to verify the application rate. The overall check can be conducted by checking the distance of area over which a truckload of a stabilizer of known weight is spread.

Assessment of QC/QA Method

Accuracy and Precision

Comments: The accuracy and precision is dependent on the experience of the field inspector.

Rating: L-M

Adequacy of Coverage

Comments: According to PCA (1980), for spot check a canvas is placed in an area of 1 m^2 (1 yd^2). Overall check can cover the distance of area over which a truckload of cement of known weight is spread

Rating: L-M

Implementation Requirements

Comments: Some experience is necessary to conduct the check.

Rating: M

Applicability to Method Approach Specifications

Comments: Spot or overall check is not applicable for method specification.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: The quality of project can be accessed by those methods.

Rating: H

Usefulness of QC/QA Method for Application

General Comments According to the Army and Air Force (1994), field personnel should be aware of quantities of stabilizer required per linear foot (meter) or per square yard (meter) of pavement. Spot check can be used to assure that the proper quantity of cement is being applied, by using a canvas of known area or, as an overall check, the area over which a known tonnage has been spread.

Pavement Foundation Stabilization

Comments: The quality of the mixing can ensure the performance of pavement foundation.

Rating: M

Construction Working Platforms

Comments: The quality of the mixing can ensure the performance of construction working platforms.

Rating: M

Compaction

Comments:

Rating: N

Void Filling

Comments:

Rating: N

Recycling/Reuse

Comments:

Rating: N

Drainage

Comments:

Rating: N

Moisture Barrier/Separation Layer

Comments:

Rating: N

Support of Embankments or Structures

Comments:

Rating: M

Liquefaction Mitigation

Comments:

Rating: N

Settlement Reduction

Comments:

Rating: M

Thickness Reduction of Pavement Section

Comments:

Rating: L

Prolonging of Pavement Service Life

Comments: The quality of the mixing can ensure the long term performance of pavement.

Rating: M

QC/QA METHOD:	**Chemical Analysis**
REFERENCE(S):	**Austroads (1998), Qubain et al. (2006)**

Method Summary: This method is used to evaluate element and mineralogy constituents of stabilized soil and a stabilizer using x-ray fluorescence (XRF) and x-ray diffraction (XRD).

Assessment of QC/QA Method

Accuracy and Precision

Comments: *It depends on the number of tests.*

Rating: *M*

Adequacy of Coverage

Comments: *Only representative samples are tested.*

Rating: *M*

Implementation Requirements

Comments: *X-ray fluorescence testing requires some experience and knowledge to conduct the test. The test is slow and expensive.*

Rating: *M*

Applicability to Method Approach Specifications

Comments: *This method is applicable to verify the stabilizer (e.g. kiln dust) to check if it meets material specifications.*

Rating: *M*

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: *Test results can help assess the quality of the project during construction.*

Rating: *M*

Usefulness of QC/QA Method for Application

General Comments Chemical analysis is used for lime, cement and fly ash content verification for uncured mixture, as well as measurement of binder content.

Pavement Foundation Stabilization

Comments: *The quality of the mixing can ensure the performance of pavement foundation.*

Rating: *M*

Construction Working Platforms

Comments: *The quality of the mixing can ensure the performance of construction working platforms.*

Rating: *M*

Compaction

Comments:

Rating: *N*

Void Filling

Comments:
Rating: *N*

Recycling/Reuse
Comments:
Rating: *N*

Drainage
Comments:
Rating: *N*

Moisture Barrier/Separation Layer
Comments:
Rating: *N*

Support of Embankments or Structures
Comments:
Rating: *M*

Liquefaction Mitigation
Comments:
Rating: *N*

Settlement Reduction
Comments:
Rating: *M*

Thickness Reduction of Pavement Section
Comments:
Rating: *M*

Prolonging of Pavement Service Life
Comments: *The quality of the mixing can ensure the long term performance of pavement.*
Rating: *M*

QC/QA METHOD:	Nuclear Gauge Method
REFERENCE(S):	**Austroads (1998), Little (1995), Qubain et al. (2006), PCA (1980), TRB (1987), White et al. (2005)**

Method Summary: The nuclear gauge method is commonly used to determine compacted field density and moisture content of stabilized soil (ASTM D2922, D3017 and D6938, AASHTO T238 and T239). This is a nondestructive test and can be performed in a matter of a few minutes.

Assessment of QC/QA Method

Accuracy and Precision

Comments: Based on repeatability measurements from a single operator, ASTM D6938 reports a standard deviation for wet density measurements as 0.3 to 1.2 lb/ft3 and for moisture content as 0.3 to 0.5% depending on the soil type and test method used (direct transmission or back scatter).

Rating: M-H

Adequacy of Coverage

Comments: Nuclear moisture/density tests are taken at several locations at intervals of 150 m (500 feet) in the field.

Rating: L

Implementation Requirements

Comments: Proper operation, calibration and maintenance of the equipment are essential. Operator teaching and license is required.

Rating: M

Applicability to Method Approach Specifications

Comment: Nuclear gauge method is not applicable for method specifications.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: Can be used to monitor and ensure the quality of the project during construction.

Rating: L-M

Usefulness of QC/QA Method for Application

General Comments The nuclear gauge method can be used to determine moisture content of materials at the time construction starts and during processing. Density of field material is checked regularly as well. This method cannot measure density of soil at depths greater than 250 mm to 300 mm (10 in. and 12 in.) below the surface. Comparing laboratory compaction test results with the field moisture-density can provide an indicator to ensure sufficient compaction.

Pavement Foundation Stabilization

Comments: The monitoring of moisture-density relationship is import to achieve the designated strength and overall goal.

Rating: H

Construction Working Platforms

Comments: The monitoring of moisture-density relationship is import to achieve the designated strength and overall goal.

Rating: H

Compaction

Comments:

Rating: N

Void Filling

Comments:

Rating: N

Recycling/Reuse

Comments:

Rating: N

Drainage

Comments:

Rating: N

Moisture Barrier/Separation Layer

Comments:

Rating: N

Support of Embankments or Structures

Comments:

Rating: M

Liquefaction Mitigation

Comments:

Rating: N

Settlement Reduction

Comments:

Rating: M

Thickness Reduction of Pavement Section

Comments:

Rating: L

Prolonging of Pavement Service Life

Comments: The monitoring of moisture-density relationship is import to achieve the designated strength and overall goal.

Rating: H

QC/QA METHOD:	Visual Inspection
REFERENCE(S):	Army and Air Force (1994), PCA (1980)

Method Summary: Trenches may be dug for visual inspection to evaluate depth and uniformity of mixing. If the soil has uniform color that indicts thorough mixing.

Assessment of QC/QA Method

Accuracy and Precision
Comments: The accuracy and precision is dependent on the experience of the field inspector.
Rating: L-M
Adequacy of Coverage
Comments:
Rating: M
Implementation Requirements
Comments: Some experience is necessary to recognize inadequate mixing and/or lack of stabilizer.
Rating: M
Applicability to Method Approach Specifications
Comments: Visual inspection is not applicable for method specification.
Rating: L
Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)
Comments: Visual inspection can be used to monitor the quality of the project during and after construction.
Rating: M

Usefulness of QC/QA Method for Application

General Comments The depth and uniformity of mixing can be checked by visual inspection. If the mixing is adequate, soil will present a uniform color. On the contrary, a streaked appearance indicates nonuniform mixing.

Pavement Foundation Stabilization
Comments:
Rating: M
Construction Working Platforms
Comments:
Rating: M
Compaction
Comments:
Rating: N
Void Filling

Comments:
Rating: *N*
Recycling/Reuse
Comments:
Rating: *N*
Drainage
Comments:
Rating: *N*
Moisture Barrier/Separation Layer
Comments:
Rating: *N*
Moisture Barrier/Separation Layer
Comments:
Rating:
Support of Embankments or Structures
Comments:
Rating: *M*
Liquefaction Mitigation
Comments:
Rating: *N*
Settlement Reduction
Comments:
Rating: *M*
Thickness Reduction of Pavement Section
Comments:
Rating: *L*
Prolonging of Pavement Service Life
Comments:
Rating: *M*

QC/QA METHOD:	**Dynamic Plate Load Tests**
REFERENCE(S):	**Christopher (2006), Qubain et al. (2006), Vennapusa and White (2009),White et al. (2005)**

Method Summary: Light weight deflectometer (LWD), falling weight deflectometer (FWD), and Clegg hammer tests fall under this category. LWD and FWD tests are performed by obtaining plate deflections under dynamic impulse loading. LWD tests apply relatively lower applied contact stresses (about 0.2 MPa or less) compared to FWD testing (applied contact stresses up to 1.0 MPa). FWD tests are often performed with an array of deflection sensors spaced away from the loading source to develop deflection basin data to assess the stiffness/modulus of the subsurface layers down to a depth of about 2 m. Clegg hammer test involves measuring hammer decelerations (g's) under impulse loading (ASTM D5874).

FWD equipment is trailer-mounted and pulled with a suitable vehicle. LWD and Clegg hammer devices come in an enclosed box and can be carried in a truck. LWD and FWD are available commercially by several manufacturers. Although the methodology of the test is similar, different manufacturers use different type of measurement sensors to measure deflections (geophones or accelerometers or sensiometers). For LWD testing, some devices assume a constant load while some devices use a load cell to measure the applied load. These differences between device configurations affect the modulus value. LWDs are generally setup with 200 and 300 mm diameter plates, while FWDs are generally setup with 300 and 450 mm diameter plates. The modulus values are affected by the plate diameter and applied contact stresses. Additional information about factors affecting the dynamic modulus values is documented in Vennapusa and White (2009).

Assessment of QC/QA Method

Accuracy and Precision

Comments: These tests are generally considered repeatable. The values may vary depending on the type of the device and deflection sensors used in the test (e.g., sensiometers, geophones, or accelerometers). Results from FWD tests have been widely in the US for direct measurement on the pavement foundation material properties.

Rating: M-H

Adequacy of Coverage

Comments: Number of tests depends on the variability observed, but generally it requires many tests to adequately characterize the spatial variability of soils. These tests are relatively fast to perform (approximately < 5 min per test). LWD and Clegg hammer tests have relatively shallow measurement depth (i.e., ≤ 0.5 m) compared to FWD tests (which provide information up to about 2 m).

Rating: M

Implementation Requirements

Comments: Experience and special equipment are necessary. Use of LWD and Clegg hammer generally requires less training and they are less expensive compared to FWD.

Rating: M

Applicability to Method Approach Specifications

Comments:

Rating: *L*

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: *Provides a direct measurement of a design-related parameter and therefore is applicable to performance approach specifications. But performance-based specifications do not exist. This can be used as an end-result specification as well.*

Rating: *M*

Usefulness of QC/QA Method for Application

General Comments This test method provides a direct measure of dynamic elastic modulus and can serve as a QC/QA tool.

Pavement Foundation Stabilization

Comments: *The stability of pavement material can ensure the quality of pavement foundation.*

Rating: *H*

Construction Working Platforms

Comments: *The stability of pavement material can ensure the quality of construction platforms.*

Rating: *H*

Compaction

Comments:

Rating: *N*

Void Filling

Comments:

Rating: *N*

Recycling/Reuse

Comments:

Rating: *N*

Drainage

Comments:

Rating: *N*

Moisture Barrier/Separation Layer

Comments:

Rating: *N*

Support of Embankments or Structures

Comments:

Rating: *H*

Liquefaction Mitigation

Comments:

Rating: *N*

Settlement Reduction

Comments:

Rating: *H*

Thickness Reduction of Pavement Section

Comments: *The design thickness of a base or subbase course can be reduced if the stabilized material meets the specified strength.*

Rating: *H*

Prolonging of Pavement Service Life

Comments: *The stability of pavement material can ensure the long term performance of pavement.*

Rating: *H*

QC/QA METHOD:	Dynamic Cone Penetrometer Test
REFERENCE(S):	Christopher et al. (2006), Qubain et al. (2006)

Method Summary: Dynamic cone penetration (DCP) test is used to assess the compaction improvement depth by comparing before and after stabilization. DCP is generally used in pavement foundation layer construction QA process and can measure soil properties up to about 2 m. Difficulties with these test procedures are documented in the literature when large particles or boulders are encountered in the subsurface.

DCP test method is described in ASTM D6951. DCP test method involves driving a cone tip into the soil by lifting a 8 kg sliding hammer to 575 mm drop height and then releasing it. The total penetration for a given number of blows is then measured and recorded as mm/blow (penetration resistance). ASTM D6951 provides correlations between California bearing ratio (CBR) and mm/blow for different soil types.

Assessment of QC/QA Method

Accuracy and Precision

Comments: For subsurface conditions with large boulders or rocks, testing may be difficult. ASTM D6951 indicates that the repeatability standard deviation of the DCP test is less than 2 mm/blow.

Rating: M

Adequacy of Coverage

Comments: It can determine the soil condition locally, and more or less tests are needed depending on the site conditions.

Rating: M

Implementation Requirements

Comments: The equipment is easy to operate, and the test requires minimal training and some experience.

Rating: M

Applicability to Method Approach Specifications

Comments: Dynamic cone penetrometer test is not applicable for method specification.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: Dynamic cone penetrometer test is used as verification test of stiffness on the field.

Rating: H

Usefulness of QC/QA Method for Application

General Comments Empirical correlations can be used to relate results from the penetration tests to soil engineering properties (e.g., soil strength, bearing capacity, stiffness/modulus, liquefaction susceptibility, etc.). These test methods are useful for QA. These methods can also be used for QC to assess improvements in subsurface conditions with increasing pass.

Pavement Foundation Stabilization
Comments: The stability of pavement material can ensure the quality of pavement foundation.
Rating: H

Construction Working Platforms
Comments: The stability of pavement material can ensure the quality of construction working platforms.
Rating: H

Compaction
Comments:
Rating: N

Void Filling
Comments:
Rating: N

Recycling/Reuse
Comments:
Rating: N

Drainage
Comments:
Rating: N

Moisture Barrier/Separation Layer
Comments:
Rating: N

Support of Embankments or Structures
Comments:
Rating: H

Liquefaction Mitigation
Comments:
Rating: N

Settlement Reduction
Comments:
Rating: L

Thickness Reduction of Pavement Section
Comments: The design thickness of a base or subbase course can be reduced if the stabilized material meets the specified strength.
Rating: H

Prolonging of Pavement Service Life
Comments: The stability of pavement material can ensure the long term performance of pavement.
Rating: H

QC/QA METHOD:	**Static Plate Load Tests**
REFERENCE(S):	**Vennapusa and White (2009)**

Method Summary: Static plate load tests involve obtaining load versus deflection curves to determine modulus of subgrade reaction or soil elastic modulus or soil bearing capacity. The test is conducted by increasing a static load on the soil and recording the corresponding plate deflections. ASTM D1195-93 standard describes the test method to perform repetitive static plate load tests of soil for evaluation and design of airport and highway pavements. AASHTO T-222 describes standard method for non-repetitive static plate load test of soils and flexible pavement components.

Assessment of QC/QA Method

Accuracy and Precision

Comments: The test is widely accepted in geotechnical engineering. ASTM D1195-93 indicates that the precision of this test method could not be determined due to the variability associated with soils and the accuracy of the test method could not be determined as there was no reference test available for comparison.

Rating: M-H

Adequacy of Coverage

Comments: Sufficient evaluation requires many tests.

Rating:L

Implementation Requirements

Comments: Experience and special equipment is necessary to produce enough reaction force for the required applied stresses. Typically, a heavy truck or a dozer or any heavy construction equipment may be used as a reaction force. A trained field engineer is required to analyze load-deflection curves and relate the measured properties with the design assumptions.

Rating: M

Applicability to Method Approach Specifications

Comments: Static PLT is not applicable for method specification.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments:

Rating: M

Usefulness of QC/QA Method for Application

General Comments This test method provides a direct measure of modulus and/or bearing capacity and can serve as a QA tool for verifying design values. Its applicability to each of the potential application is rated

Pavement Foundation Stabilization

Comments:
Rating: *H*
Construction Working Platforms
Comments: *The stability of pavement material can ensure the quality of construction working platforms.*
Rating: *H*
Compaction
Comments:
Rating: *N*
Void Filling
Comments:
Rating: *N*
Recycling/Reuse
Comments:
Rating: *N*
Drainage
Comments:
Rating: *N*
Moisture Barrier/Separation Layer
Comments:
Rating: *N*
Moisture Barrier/Separation Layer
Comments:
Rating:
Support of Embankments or Structures
Comments:
Rating: *H*
Liquefaction Mitigation
Comments:
Rating: *N*
Settlement Reduction
Comments:
Rating: *H*
Thickness Reduction of Pavement Section
Comments:
Rating: *H*
Prolonging of Pavement Service Life
Comments:
Rating: *H*

QC/QA METHOD ASSESSMENT, CONCLUDING REMARKS

The QC/QA assessments up to this point have focused on individual QC/QA methods, rather than overall QC/QA programs for this technology. This section provides an opportunity to describe how individual QC/QA methods are applied within a comprehensive QC/QA program for the technology. References should be cited where available. If adequate QC/QA methods and/or a comprehensive QC/QA program for this technology are lacking, that can be discussed in this section also.

1. Prior to stabilizer application

   Sampling of loose processed materials is used to check gradation of the materials and ensure the oversize materials are limited to the specification target value. For controlling pulverization in cement stabilization, a sieve analysis is typically performed using a No. 4 sieve. For lime stabilization, the 1-inch and No. 4 sieves are designated for controlling pulverization. Gradation requirements for fly ash and bitumen-stabilized soil are detailed in Army and Air Force (1994).

2. During stabilizer application

   Stabilizer additive content tests are performed transversely across the pavement and at various depths within the stabilized layer to assess the mixing effectiveness. Chemical analysis, phenolphthalein test, and visual inspection are used to estimate the stabilizer content. Chemical analysis can be expensive and slow, however. According to TRB (1987), a phenolphthalein test on a face cut in the stabilized layer is used as a "quick" test to determine the presence of lime or cement instead of the exact content of the stabilizer. A reddish-pink color develops if lime is present in the soil, for example.

   Trenches are dug and a visual inspection is made to assure uniformity of the mixture. Uniformity is checked throughout the depth and across the width of the pavement. The phenolphthalein test can also be used to check the uniformity of the mixture in the field.

   Moisture content measurements are obtained at various stages of construction. Moisture content is commonly determined by either oven-dry or nuclear gauge methods. The hand-squeeze test is not frequently mentioned, but often used to estimate suitable moisture content. Although the hand-squeeze test cannot replace the standard moisture content test, it assists with improved process control. The control of moisture content is important in achieving required pulverization and hydration for lime, cement, and fly ash stabilization. Bitumen stabilization has specified requirements for moisture content.

   Field personnel should be aware of the depth of the stabilized layers both before and after compaction. Depth of mixing can be checked as the same time as uniformity, and should be checked routinely during mixing operations.

3. In-situ verification

   Nuclear gauge testing is common for checking if the required dry density is obtained after compaction. Clegg impact hammer and dynamic cone penetrometer (DCP) tests are two methods to measure the stability of the stabilized subgrade at various times upon completion of stabilization. In addition, undisturbed samples following a laboratory curing process can be used to determined unconfined compressive strength and resilient modulus in the laboratory.

APPENDIX C: TASK 12 ASSESSMENT OF EXISTING SPECIFICATION

TASK 12 ASSESSMENT OF EXISTING SPECIFICATIONS
CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES

ASSESSOR(S): WENJUAN LI
ASSESSMENT REVIEWER(S): DAVID WHITE
ADDITIONAL REVIEWER(S):
DATE OF THIS ASSESSMENT: 06/20/2011
FILE NAME FOR THIS VERSION: CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES_TASK 12_06 2011_FORPEERREVIEW.DOC

TABLE OF CONTENTS

INTRODUCTION

BACKGROUND INFORMATION

Existing specifications from a variety of sources (FHWA documents, individual project documents in the public record, industry guide specifications, etc.) will be collected and evaluated in the Strategic Highway Research Program's (SHRP2) research project R02, "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of Pavement Working Platform." Some technologies already have well-written example specifications, some have a variety of different types of specifications, and others only have specifications that have been written for specific projects. The objective of this task is to provide/develop high-quality sample guide specifications to facilitate widespread use of soil improvement technologies.

DOCUMENT PURPOSE

This document provides instructions and a template for assessing and characterizing published specifications for technologies that are applicable to Elements 1, 2, and 3 of the SHRP2 R02 project. Element 1 addresses new embankments and roadways constructed over unstable soils, Element 2 addresses widening of existing roadways and embankments, and Element 3 addresses stabilization of pavement working platforms. The assessments and characterizations in this document will be used to complete other work items associated with Task 12, as described in the Phase 2 work plan in the Phase 1 report.

DESCRIPTION OF DOCUMENT CONTENTS

The first section provides instructions and matrices for characterizing the available specifications as either method, performance, or performance/method approach specifications and by performance level. Descriptions of these three categories of specifications and performance levels are given in the instructions.

The characterization section is followed by a section that provides instructions and a matrix for assessing the completeness of the specifications.

The completeness section is followed by two sections that assess the specification for factors such as clarity, risk allocation, ability to be fairly bid, constructability, QC/QA verification, and completeness. The first section includes instructions and a matrix for assessing the specification based on these factors. The second section provides any comments about the assessment.

The assessment sections are followed by a section where concluding remarks about the available specifications can be made.

After an assessment is completed there may be a decision to develop a guide specification. If so, previously developed guide specifications should serve as examples of the typical layout and commentary to be followed. Good guide specification examples include the "Standard Performance Approach Specification for Vibro-Concrete Columns" and the "SMSE Performance Spec." It should be noted that specification sections and subsections are technology dependent. Their organization and content should be determined on a case-by-case basis and need not be consistent with the example guide specifications.

SPECIFICATION TYPE, INSTRUCTIONS

The following matrix is used to list the available specifications, the references from which they were obtained, and to indicate the specification type. Each portion of the matrix is described below as well as the descriptions for each specification type.

REFERENCES

Each reference containing a specification should be listed in author (date) format in this portion of the matrix. Some references may include multiple specifications. Complete citations for the references can be found in the technology's bibliography document. However, many of the specifications will not be from a referenced source but rather provided by a State DOT, engineer or contractor. The source of each specification will be identified.

SPECIFICATION TYPE

In this portion of the matrix a designation should be provided to indicate the specification type. Specification type refers to both the specification category (i.e., method approach, performance approach, or performance/method approach) and, for specifications with performance elements, the performance level provided for in the specification. To indicate specification category, a check should be inserted in the corresponding row for each specification. For performance approach specifications and performance/method approach specifications, it is also necessary to indicate the performance level based on the designations below.

DESCRIPTIONS AND DESIGNATIONS

Method Approach Specifications

Method approach specifications require the contractor to produce and place a product using specified materials in definite proportions and with specific types of equipment and methods. The agency is responsible for performance provided that the contractor has followed the specified methods[1].

Performance Approach Specifications

Definitions for types of performance approach specifications are not always consistent[2]. *For the purposes of this project, the performance levels defined below have been adopted to differentiate between the various types of performance approach specifications. In addition, it should be noted that any performance approach specification may also include provisions for statistical sampling or incentives based on time and quality of construction.*

Performance level refers to the manner in which a specification requires performance characteristics to be measured in order to determine project acceptance. Performance levels have been separated based on the following designations:

1 - *Actual performance measured after construction (e.g., settlement at a specific time) and warranty provisions might be included*

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[1] *http://www.fhwa.dot.gov/construction/specs.cfm, TRB Circular E-C074, and FHWA NHI-05-037 Section 8.2*
[2] *http://www.fhwa.dot.gov/construction/specs.cfm, TRB Circular E-C074, and FHWA NHI-05-037 Section 8.2*

2 - *Performance-related properties measured at end of construction (e.g., CPT, vane shear, etc.)*
3 - *Design properties measured during construction (e.g., modulus measured for each lift)*
4 - *Design-related properties measured during construction (e.g., density and water content measured for each lift)*

Single or combined designations should be used as applicable based on the descriptions. An example of a combined designation for a specification that measures performance characteristics based on both design (3) and design-related properties (4) would be 3/4.

Performance/Method Approach Specifications

Performance/method approach specifications contain a combination of method and performance or design related requirements. These specifications often include minimum geometric requirements and also require that minimum performance characteristics are satisfied.

		Specification Name/Number								
		Lime Stabilized Sugrade/Base Course	Cement Stabilized Subgrade/Base Course	Flyash Stabilized Subgrade/Base Course	Asphalt Stabilized Subgrade/Base Course	Lime-Fly ash stabilized Subgrade/Base Course				
Specification Type	METHOD APPROACH	✔	✔	✔	✔	✔				
	PERFORMANCE APPROACH									
	COMBINED PERFORMANCE/ METHOD APPROACH	✔	✔	✔	✔	✔				
	PERFORMANCE LEVEL	2/3/4	2/3/4	2/3/4	2/3/4	2/3/4				
REFERENCES/SOURCE[3]	AASHTO (2008)	✔	✔							
	ACAA (2008)			✔						
	Alabama DOT (2008)	✔								
	Alaska DOT (2004)				✔					
	Alberta Infrastructure and Transportation (2007)		✔		✔					
	Arkansas DOT (2003)	✔	✔							
	California DOT (2006)	✔	✔							
	City of College Station (2009)	✔	✔							
	Colorado DOT (2005)	✔								
	Delaware DOT (301)				✔					
	FHWA (2009)	✔	✔	✔	✔	✔				
	Florida DOT (2010)	✔	✔		✔					
	Georgia DOT (2001)	✔	✔		✔					
	Illinois DOT (2007)	✔	✔							
	Kansas DOT (2007)	✔	✔	✔						

[3] Complete citations for the references shown above can be found in the bibliography document for this technology.

		Specification Name/Number								
		Lime Stabilized Sugrade/Base Course	Cement Stabilized Subgrade/Base Course	Flyash Stabilized Subgrade/Base Course	Asphalt Stabilized Subgrade/Base Course	Lime-Fly ash stabilized Subgrade/Base Course				
Specification Type	METHOD APPROACH	✓	✓	✓	✓	✓				
	PERFORMANCE APPROACH									
	COMBINED PERFORMANCE/ METHOD APPROACH	✓	✓	✓	✓	✓				
	PERFORMANCE LEVEL	2/3/4	2/3/4	2/3/4	2/3/4	2/3/4				
REFERENCES/SOURCE[4]	Little (1995)	✓								
	Louisiana DOT (2006)	✓	✓							
	New Mexico DOT (2007)	✓	✓							
	New York State DOT (2008)	✓	✓		✓					
	North Carolina DOT (2002)	✓	✓							
	North Dakota DOT (2008)		✓		✓					
	Oklahoma DOT (2009)	✓	✓	✓						
	Oregon DOT (2008)	✓	✓							
	Pennsylvania DOT (2006)	✓		✓						
	Prince William County (2006)	✓								
	Sacomaine.org (2000)	✓	✓	✓						
	South Carolina DOT (2007)		✓		✓					
	Tennessee DOT (2006)	✓	✓		✓	✓				
	Texas DOT (2004)	✓		✓	✓	✓				
	Vermont Agency of Transportation (2006)				✓					

[4] Complete citations for the references shown above can be found in the bibliography document for this technology.

		Specification Name/Number								
		Lime Stabilized Sugrade/Base Course	Cement Stabilized Subgrade/Base Course	Flyash Stabilized Subgrade/Base Course	Asphalt Stabilized Subgrade/Base Course	Lime-Fly ash stabilized Subgrade/Base Course				
Specification Type	METHOD APPROACH	✓	✓	✓	✓	✓				
	PERFORMANCE APPROACH									
	COMBINED PERFORMANCE/ METHOD APPROACH	✓	✓		✓					
	PERFORMANCE LEVEL	2/3/4	2/3/4		2/3/4					
REFERENCES/SOURCE[5]	Virginia DOT (2007)	✓	✓		✓					
	Wyoming DOT (2003)	✓								

[5] Complete citations for the references shown above can be found in the bibliography document for this technology.

The following matrix should be filled out to determine the completeness of the specification. A check mark should be placed in the box to show that a section is present in the specification. If there are additional important sections, these can be added to the matrix. This could include adding subsections that are important and should be included in all the specifications for a specific technology. The section titles listed below may not match exactly to a section in the specification, but if the information is included anywhere in the specification a check should be placed in the corresponding box. In addition, some of the sections listed below may not be applicable to the technology. If this is the case, N/A should be placed the corresponding box.

The following definitions apply to the standard sections listed in the matrix below.

Project Objectives: This section describes the project and the reasons for employing the soil improvement/geoconstruction technology.
Site Conditions: This section describes the construction site including the subsurface conditions, extents of the proposed soil improvement/geoconstruction and any special conditions or requirements.
References: This section lists the standards including ASTM and/or AASHTO standards that are referenced in the specification.
Definitions: This section defines any terms not commonly used or defined elsewhere in the contract.
Minimum Contractor Qualifications: This section lists the required qualifications that the contractor must possess.
Submittals: This section provides a list of the required submittals as well as due dates. The following sub-sections are used to specify the type of submittals required.

> **Material:** This may include a material sample, manufacturer or mill certificate, fabricator certificate, and/or lab test results that can be used to verify the appropriateness of the material for the project and/or that certifies the material meets all project requirements.
> **Design:** This may include calculations and shop drawings that demonstrate the proposal meets the design and/or geometric requirements. It may also include certificates from the manufacturer stating that the product meets project requirements.
> **Construction:** This may include certificates from the contractor or design engineer stating that the project has been constructed as proposed and/or that all project requirements have been met upon completion. It may also include QC test reports and summaries submitted during construction.

Accepted Systems: This section describes the systems that have been approved for use during construction. For example, with mechanically stabilized earth walls the owner may have a list of approved MSE wall systems.
Pre-Construction Meeting: This section gives the details of any required pre-construction meetings including location, time in relation to other contract requirements and participants.
Design Requirements: This section is only applicable to performance and performance/method approach specifications, and it describes the requirements that must be satisfied by contractor design of the soil improvement/geoconstruction technology, such as bearing capacity, factor of

safety, settlement, etc. The following sub-sections may also be included when the specifications require design by the contractor:

> **Design Methodology:** This sub-section identifies the procedure(s) that should be followed during the design of the soil improvement/geoconstruction technology.
>
> **Field Geotechnical Conditions:** This sub-section lists the values of geotechnical parameters that should be used in the design. If values are not provided by the owner, this could affect the ability of the project to be fairly bid and should be commented on in the Specification Assessment.

Material Requirements: This section lists the requirements for the materials used during construction.

Geometric Requirements: This section describes the required geometry that must be satisfied during construction.

Equipment: This section lists any equipment required for construction.

Construction Requirements: This section describes any required construction methods and procedures that must be followed.

QC/QA Requirements: This section explains any required QC/QA tests as well as the frequency and location of the tests. If a test should be performed with an unusual method, it will also be discussed in this section.

Acceptance Criteria: This section lists the criteria and methods of measurement for acceptance. For method approach specifications, this includes acceptance based on conformance to construction/design requirements such as equipment or dimensional requirements. It may also include acceptance based on conformance to quality control requirements, for example, as determined by review of quality control records. For performance approach specifications (by performance level), this could include acceptance based on: **(1)** conformance to performance requirements such as capacity or settlement from load tests after construction, **(2)** conformance to performance-related requirements such as CPT or vane shear values measured at end of construction, **(3)** conformance to design properties such as modulus values measured during construction for each lift, or **(4)** conformance to design-related properties such as values of density and water content measured during construction for each lift. Method/performance approach specifications and specifications with multiple performance levels should contain a combination of the above listed acceptance criteria as appropriate.

Maintenance: This section lists any required maintenance that must occur after construction is complete.

Measurement: This section describes how the construction work will be measured for payment.

Payment: This section describes how the contractor will be paid for the work.

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TASK 12 ASSESSMENT
SPECIFICATION COMPLETENESS, MATRIX

Sections Included	Specification Name/Number						
	Lime Stabilized Sugrade/Base Course	Cement Stabilized Subgrade/Base Course	Flyash Stabilized Subgrade/Base Course	Asphalt Stabilized Subgrade/Base Course	Lime-Fly ash stabilized Subgrade/Base Course		
PROJECT OBJECTIVES	✓	✓	✓	✓	✓		
SITE CONDITIONS	✓	✓	✓				
REFERENCES	✓	✓		✓			
DEFINITIONS	✓	✓		✓			
MINIMUM CONTRACTOR QUALIFICATIONS	✓	✓					
SUBMITTALS	✓	✓	✓	✓	✓		
└MATERIAL	✓	✓	✓	✓	✓		
└DESIGN	✓	✓	✓	✓	✓		
└CONSTRUCTION	✓	✓	✓	✓	✓		
CERTIFICATES	✓	✓					
ACCEPTED SYSTEMS							
PRE-CONSTRUCTION MEETING							
PERFORMANCE REQUIREMENTS	✓						
DESIGN REQUIREMENTS	✓	✓		✓	✓		
└DESIGN METHODOLOGY	✓	✓		✓	✓		
└FIELD GEOTECHNICAL CONDITIONS	✓	✓		✓			
MATERIAL REQUIREMENTS	✓	✓	✓	✓	✓		
EQUIPMENT	✓	✓	✓	✓	✓		
CONSTRUCTION REQUIREMENTS	✓	✓	✓	✓	✓		
QC/QA REQUIREMENTS	✓	✓	✓	✓			
ACCEPTANCE CRITERIA	✓	✓		✓			
MAINTENANCE	✓	✓		✓			
MEASUREMENT	✓	✓	✓	✓	✓		
PAYMENT	✓	✓	✓	✓	✓		

A matrix has been developed to assess existing specifications for clarity, risk allocation, ability to be fairly bid, constructability, QC/QA verification, and completeness. In general, H stands for high, M for medium, and L for low. Further discussion of these ratings is described below.

Clarity

H: The specification is easy to read, logically ordered, and provides clear instructions for completing the work. There are no conflicting statements in the specification.

M: The specification has one or two conflicting statements and portions have ambiguous language.

L: There are numerous conflicting statements or the specification is incomplete or the language could be considered ambiguous.

Risk Allocation[6]

O: Risk is inappropriately allocated to the owner.

S: Risk is appropriately shared between the owner and the contractor.

C: Risk is inappropriately allocated to the contractor.

Ability to be Fairly Bid

H: Contractors can bid on the work without needing additional information and the specification allows substitution for proprietary products.

M: The specification requirements favor certain contractors or products. Contractors may find it difficult to create realistic bids because some information is lacking.

L: The specification does not provide enough information and/or multiple contractors cannot bid the project.

Constructability

H: The specification does not require overly elaborate or expensive construction methods.

M: All construction requirements are buildable, but the specified methods are unnecessarily difficult.

L: The construction requirements are very difficult or expensive to achieve.

QC/QA Verification

H: The specification contains all the detailed requirements necessary for QC/QA, as appropriate to the technology and specification type.

[6] "Appropriately shared" means that the risk has been appropriately allocated to either the contractor, the owner, or some combination of the two parties. The appropriate allocation will vary based on the type of specification. For example, the owner should bear the risk when using a method specification. In a combined method/performance specification, each party will bear part of the risk. "Inappropriately allocated to the contractor" means that the risk has been allocated to the contractor in a situation where it should be allocated to the owner. For example, in a method specification, the owner should bear the risk and not require the contractor to meet performance criteria. "Inappropriately allocated to the owner" means that substantial risk has been allocated to the owner when it should be allocated the contractor, such as in a Level I performance specification.

M: The specification includes some detailed requirements for QC/QA, as appropriate to the technology and specification type, but it only provides general guidance for other aspects of QC/QA.

L: The specification includes no guidance or only general guidance for QC/QA.

Completeness

H: The specification contains all pertinent sections, as appropriate for the technology and specification type, and it is considered complete.

M: The specification contains most of the necessary sections but is lacking some important items.

L: The specification is missing many important items.

		Specification Name/Number						
		Lime Stabilized Sugrade/Base Course	Cement Stabilized Subgrade/Base Course	Flyash Stabilized Subgrade/Base Course	Asphalt Stabilized Subgrade/Base Course	Lime-Fly ash stabilized Subgrade/Base Course		
Specification Rating	CLARITY	H	H	M	H	M		
	RISK ALLOCATION	S	S	S	S	S		
	ABILITY TO BE FAIRLY BID	M	M	M	M	M		
	CONSTRUCTABILITY	H	H	H	H	H		
	QC/QA VERIFICATION	H	H	H	H	H		
	COMPLETENESS	H	H	M	H	M		

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TASK 12 ASSESSMENT DOCUMENT
SPECIFICATION ASSESSMENT, COMMENTS

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

SPECIFICATION NAME/NUMBER:	Lime Stabilized Sugrade/Base Course
REFERENCE(S):	AASHTO (2008), Alabama DOT (2008), Arkansas DOT (2003), California DOT (2006), City of College Station (2009), Colorado DOT (2005), FHWA (2003), Florida DOT (2010), Georgia DOT (2001), Illinois DOT (2007), Kansas DOT (2007), Little (1995), Louisiana DOT (2006), New Mexico DOT (2007), New York State DOT (2010), North Carolina DOT (2002), Tennessee DOT (2006), Texas DOT (2004), Virginia DOT (2007), Wyoming DOT (2003)

Clarity

Comments: *The specifications are intended as a generic specification for stabilization and modification of subgrades/base courses. They are easy to follow and understand.*

Rating: *H*

Risk Allocation

Comments: *The contractor is responsible for material selection, mix design, QA/QC in accordance with the requirements stated in the specification. The engineer requires verifying the mix design and conducting quality assurance programs.*

Rating: *S*

Ability To Be Fairly Bid

Comments: *The contractor is able to obtain information from the specification such as material, equipment, construction method. However, the contractor may require additional information for bidding.*

Rating: *M*

Constructability

Comments: *The specifications have sections including material properties, construction method, equipment requirement, and performance criteria. They are straightforward and easy to follow.*

Rating: *H*

QC/QA Verification

Comments: *The specifications have all the detailed requirements for QC/QA. The verifications can be completed during construction and/or at the completion of construction.*

Rating: *H*

Completeness

Comments:

Rating: *H*

SPECIFICATION ASSESSMENT, COMMENTS

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

SPECIFICATION NAME/NUMBER:	Cement Stabilized Subgrade/Base Course
REFERENCE(S):	AASHTO (2008), Alberta Infrastructure and Transportation (2007), California DOT (2006), City of College Station (2009), FHWA (2003), Florida DOT (2010), Georgia DOT (2001), Illinois DOT (2007), Kansas DOT (2007), Louisiana DOT (2006), New Mexico DOT (2007), New York State DOT (2010), North Carolina DOT (2002), South Carolina DOT (2007), Tennessee DOT (2006), Virginia DOT (2007)

Clarity

Comments: *The specifications are intended as a generic specification for stabilization and modification of subgrades/base courses. They are easy to follow and understand.*

Rating: *H*

Risk Allocation

Comments: *The contractor is responsible for material selection, mix design, QA/QC in accordance with the requirements stated in the specification. The engineer requires verifying the mix design and conducting quality assurance programs.*

Rating: *S*

Ability To Be Fairly Bid

Comments: *The contractor is able to obtain information from the specification such as material, equipment, construction method. However, the contractor may require additional information for bidding.*

Rating: *M*

Constructability

Comments: *The specifications have sections including material properties, construction method, equipment requirement, and performance criteria. They are straightforward and easy to follow.*

Rating: *H*

QC/QA Verification

Comments: *The specifications have all the detailed requirements for QC/QA. The verifications can be completed during construction and/or at the completion of construction.*

Rating: *H*

Completeness

Comments:

Rating: *H*

SPECIFICATION ASSESSMENT, COMMENTS

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

SPECIFICATION NAME/NUMBER:	Flyash Stabilized Subgrade/Base Course
REFERENCE(S):	ACAA (2008), Indiana DOT (2010), Kansas DOT (2007), Oklahoma DOT (2009), Pennsylvania DOT (2006), Sacomaine.org (2000), Texas DOT (2004)

Clarity

Comments: *The specifications have intended as a generic specification for stabilization and modification of subgrades/base courses. However, some of the specifications should clarify the site condition to ensure the soils are suitable for fly ash stabilization.*

Rating: *M*

Risk Allocation

Comments: *The contractor is responsible for material selection, mix design, QA/QC with the requirements stated in the specification. The engineer requires verifying the mix design and conducting quality assurance programs.*

Rating: *S*

Ability To Be Fairly Bid

Comments: *The contractor is able to obtain information from the specification such as material, equipment, and construction method. However, the contractor may require additional information for bidding.*

Rating: *M*

Constructability

Comments: *The specifications have sections including material properties, construction method, QA/QC criteria and equipment requirement. They are straightforward and easy to follow.*

Rating: *H*

QC/QA Verification

Comments: *The specifications have all the detailed requirements for QC/QA. The verifications can be completed during construction and/or at the completion of construction.*

Rating: *H*

Completeness

Comments:

Rating: *M*

SPECIFICATION ASSESSMENT, COMMENTS

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

SPECIFICATION NAME/NUMBER:	Asphalt Stabilized Subgrade/Base Course
REFERENCE(S):	Alaska DOT (2004), Alberta Infrastructure and Transportation (2007), Delaware DOT (2001), FHWA (2009), Florida DOT (2010), Georgia DOT (2001), New York State DOT (2010), South Carolina DOT (2007), Texas DOT (2004), Vermont Agency of Transportation (2006), Virginia DOT (2007)

Clarity

Comments: *The specifications are intended as a generic specification for stabilization and modification of subgrades/base courses. They are easy to follow and understand.*

Rating: *H*

Risk Allocation

Comments: *The contractor is responsible for material selection, mix design, QA/QC with the requirements stated in the specification. The engineer requires verifying the mix design and conducting quality assurance programs.*

Rating: *S*

Ability To Be Fairly Bid

Comments: *The contractor is able to obtain information from the specification such as material, equipment, construction method. However, the contractor may require additional information for bidding.*

Rating: *M*

Constructability

Comments: *The specifications have sections including material properties, construction method, equipment requirement, and performance criteria. They are straightforward and easy to follow.*

Rating: *H*

QC/QA Verification

Comments: *The specifications have all the detailed requirements for QC/QA. The verifications can be completed during construction and/or at the completion of construction.*

Rating: *H*

Completeness

Comments:

Rating: *H*

SPECIFICATION ASSESSMENT, COMMENTS

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

SPECIFICATION NAME/NUMBER:	Lime-Fly ash stabilized Subgrade/Base Course
REFERENCE(S):	Tennessee DOT (2006), Texas DOT (2004)

Clarity

Comments: *The specifications are intended as a generic specification for stabilization and modification of subgrades/base courses. However, the specifications need to clarify the site condition to ensure that the soils are suitable for lime-fly ash stabilization.*

Rating: *M*

Risk Allocation

Comments: *The contractor is responsible for material selection, mix design, QA/QC in accordance with the requirements stated in the specification. The engineer requires verifying the mix design and conducting quality assurance programs.*

Rating: *S*

Ability To Be Fairly Bid

Comments: *The contractor is able to obtain information from the specification such as material, equipment, and construction method. However, the contractor may require additional information for bidding.*

Rating: *M*

Constructability

Comments: *The specifications have sections including material properties, construction method, and equipment requirement. They are straightforward and easy to follow.*

Rating: *H*

QC/QA Verification

Comments: *The specifications have all the detailed requirements for QC/QA. The verifications can be completed during construction and/or at the completion of construction.*

Rating: *H*

Completeness

Comments:

Rating: *M*

CHEMICAL STABILIZATION OF SUBGRADES AND BASE COURSES: TASK 12 ASSESSMENT DOCUMENT

SPECIFICATION CHARACTERIZATION, INSTRUCTION AND COMMENTS

After completing the Specification Assessment, specifications should be characterized based on the current state of the available specifications. Several specifications of each category may exist for a technology, but the intent here is to characterize the overall status of the specifications based on the previous assessments. If a specification category is not applicable to this technology, put N/A for all characterization categories. In some cases, it may be appropriate to select multiple characterization categories for a given specification category column. This might occur if multiple characterization categories are applicable for all the specifications in a given specification category. Or, for performance or performance/method approach specifications, specifications having different performance levels may also require different characterizations. If desired, the next section can be used to comment on the characterizations.

Specification Characterization Categories	METHOD APPROACH SPECIFICATION	PERFORMANCE APPROACH SPECIFICATION	COMBINED PERFORMANCE/ METHOD APPROACH SPECIFICATION
One preferred specification exists: One of the existing specifications is satisfactory and clearly preferred. No further development is needed.			
Selection guidance: More than one specification exists for this technology. Guidance is needed to select which specification is to be used. Selection of the most specification may depend on project-specific parameters.			
Combine: More than one specification exists. Specification sections may need to be combined into a single consistent recommended specification using the best elements of two or more specifications.			
Improve: An existing specification has suitable components, but improvement is needed in some areas.	✓		✓
Develop: No suitable specification exists, and a new specification must be developed.		✓	

SPECIFICATION CHARACTERIZATION, COMMENTS

The following section can be used to comment on the characterizations given in the Specification Characterization Matrix. The characterizations in this section should correspond to those given in the Specification Characterization Matrix. If a specification type is not application to this technology, this should be discussed in these comments. In addition, if one specification type is more applicable than the other, this should be mentioned.

Method Approach Specification

Comments: *Method approach specifications are available in several states for chemically stabilized pavement projects. Performance criteria should be clarified in the specification.*

Characterization: *Improve*

Performance Approach Specification

Comments: *Performance approach specifications are needed to be developed.*

Characterization: *Develop*

Combined Performance/Method Approach Specification

Comments: *Combined performance and method approach specifications are used for chemically stabilization subgrades/base courses.*

Characterization: *Improve*

ADDITIONAL COMMENTS AND CONCLUDING REMARKS

This section provides an opportunity to make any additional comments and conclusions about the specifications that were reviewed. These comments and conclusions may include a discussion of the quality of the specifications, the suitability of the specifications for use in developing guide specification examples for certain specification types, and any additional information that may be needed to create the guide specification examples. The reviewer should also comment as to whether all the necessary QC/QA procedures listed in the guidelines developed during the Task 10 Assessment are included in the reviewed specifications. These comments should include listing any QC/QA procedures that are not included in the specifications and whether the frequency or other portion of the procedure described in the specifications should be changed to match the guidelines from the Task 10 Assessment document.

After reviewing the specifications, comments are the following:

(1) Generally, performance specifications are not used for chemical stabilization projects, since no suitable testing methods exist for measuring the long-term performance of stabilized pavements right after construction. Specifications for combined chemical stabilization methods (e.g lime/fly ash) are available in few state DOTs.

(2) Available specifications for fly ash and lime/fly ash stabilization methods are lacking completeness. Based on the specification matrix, some important sections should include such as acceptance criteria, minimum contractor qualifications, etc.

(3) Some QA/QC testing methods are not well described in reviewed specifications.

APPENDIX D: SEM IMAGES OF SUBGRADES NOT SHOWN IN CHAPTER 4

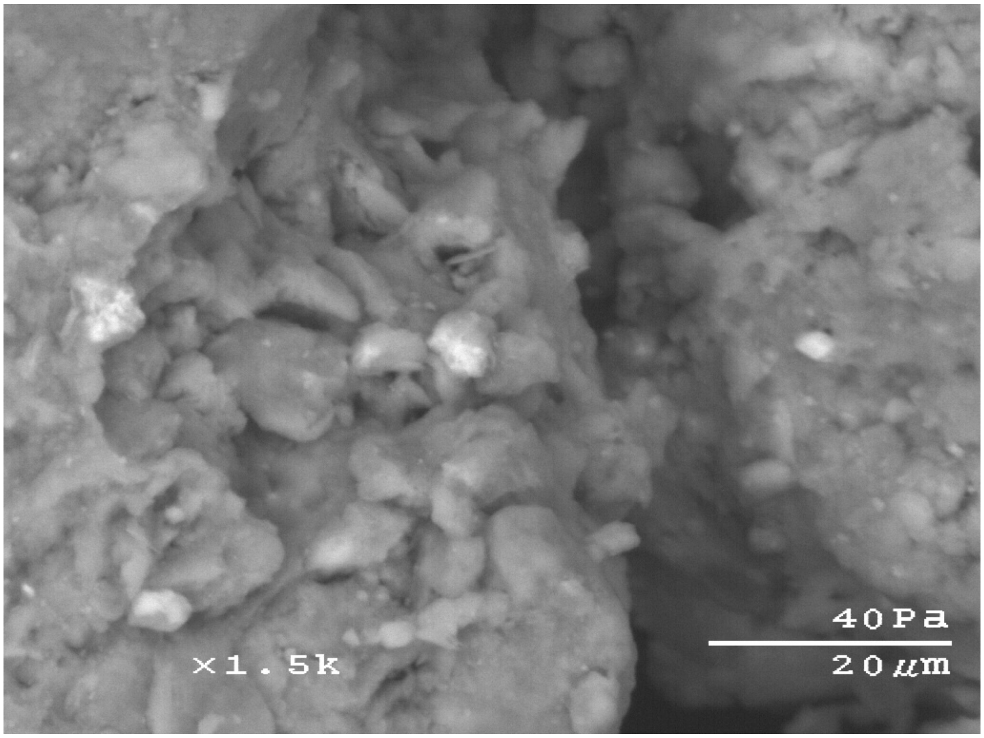

Figure 146. SEM image of stabilized subgrade in area b (1500 ×) – SH 121

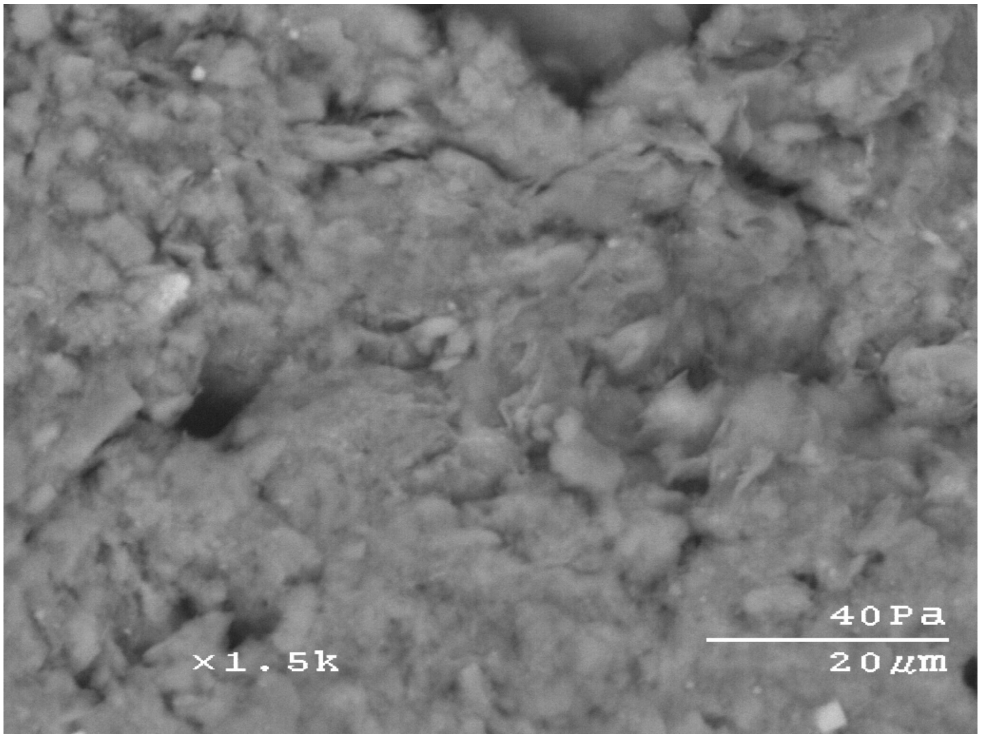

Figure 147. SEM image of stabilized subgrade (1500 ×) – FM 1709

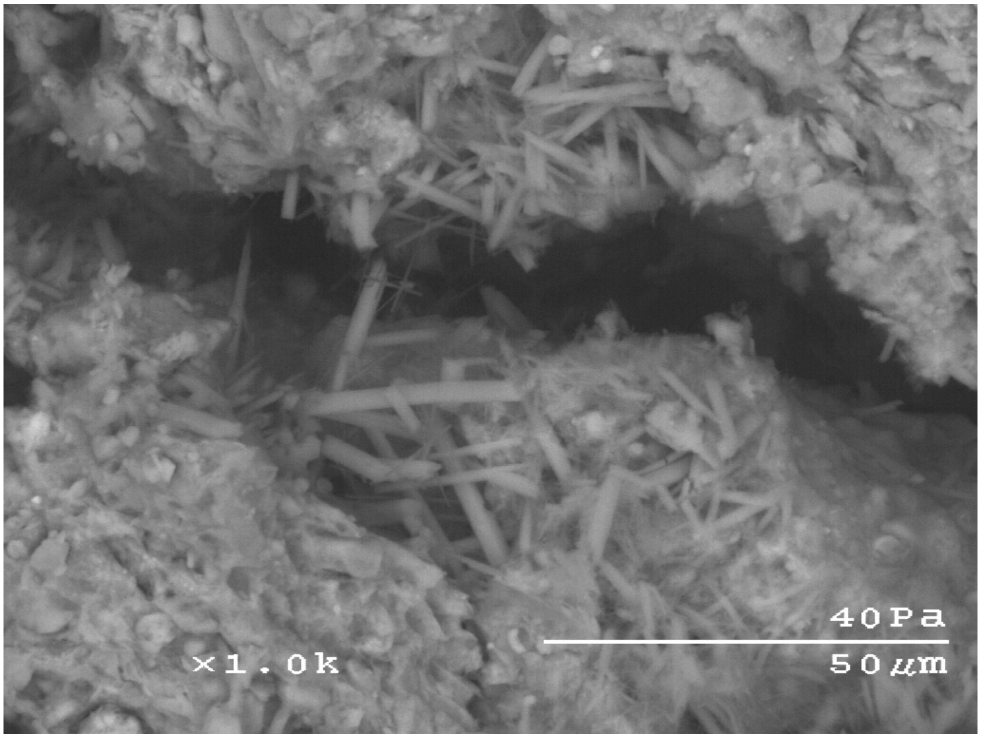

Figure 148. SEM image of stabilized subgrade in area b (1000 ×) – US 287

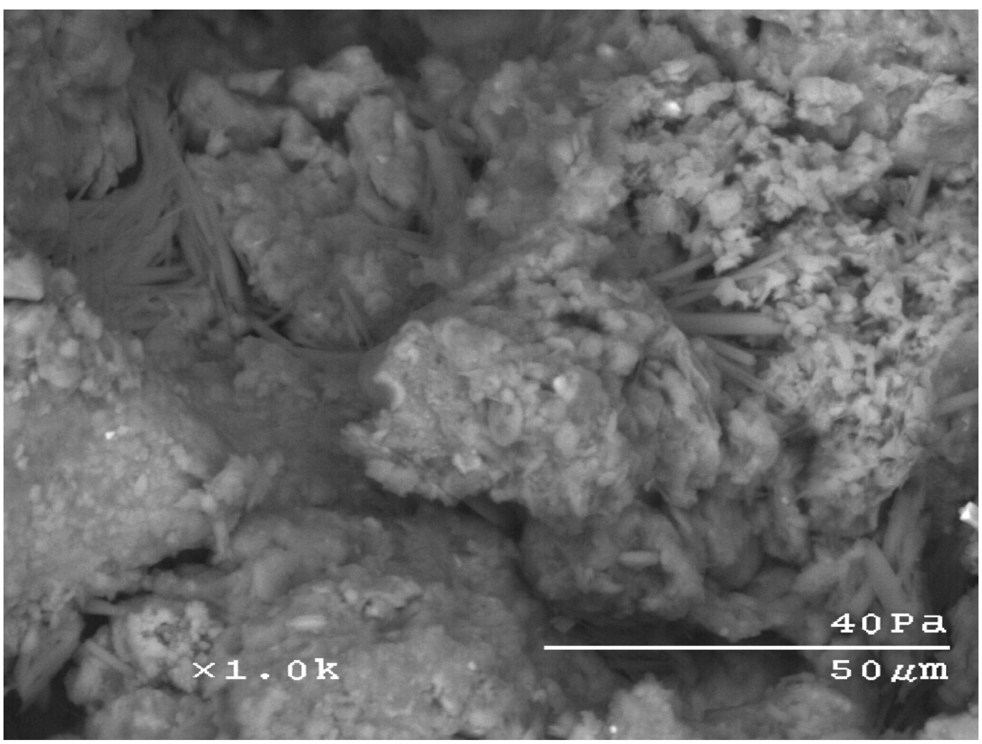

Figure 149. SEM image of stabilized subgrade (1000 ×) – US 287

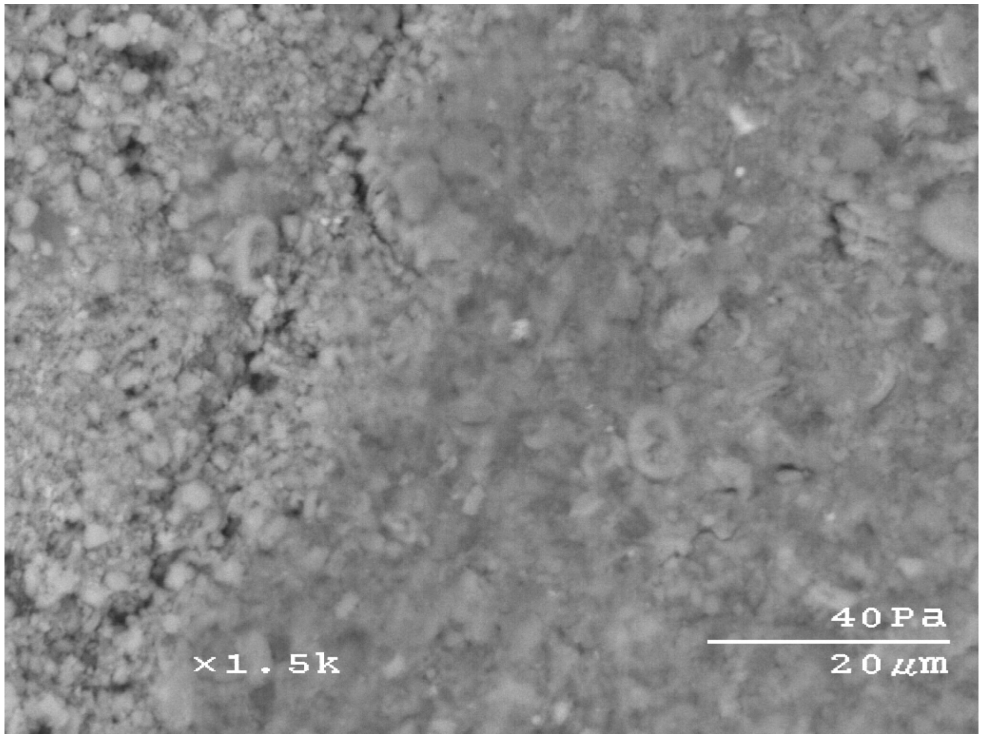

Figure 150. SEM image of stabilized subgrade (1500 ×) – US 287

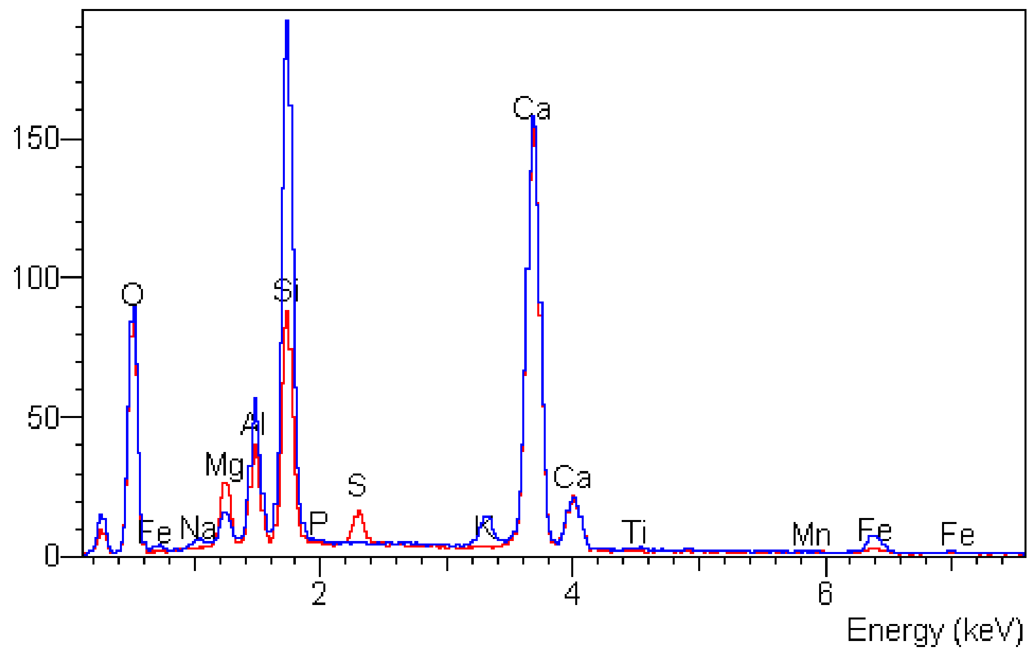

Figure 151. EDS intensity counts for stabilized subgrade sample in area a and stabilized subgrade sample in area b (red line 500×; blue line 500×) – US 183

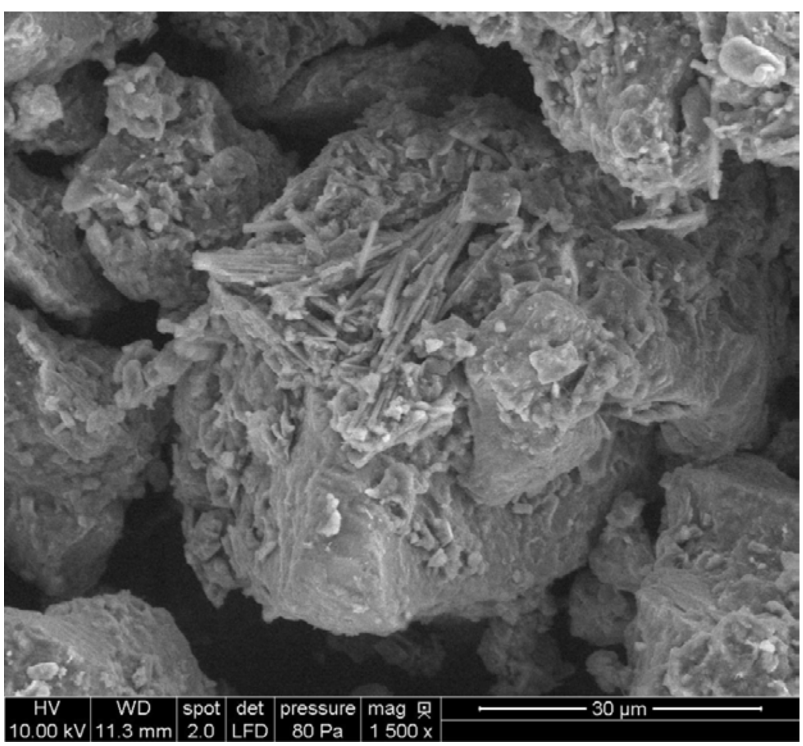

Figure 152. SEM image of natural subgrade (1500 ×) – US 183

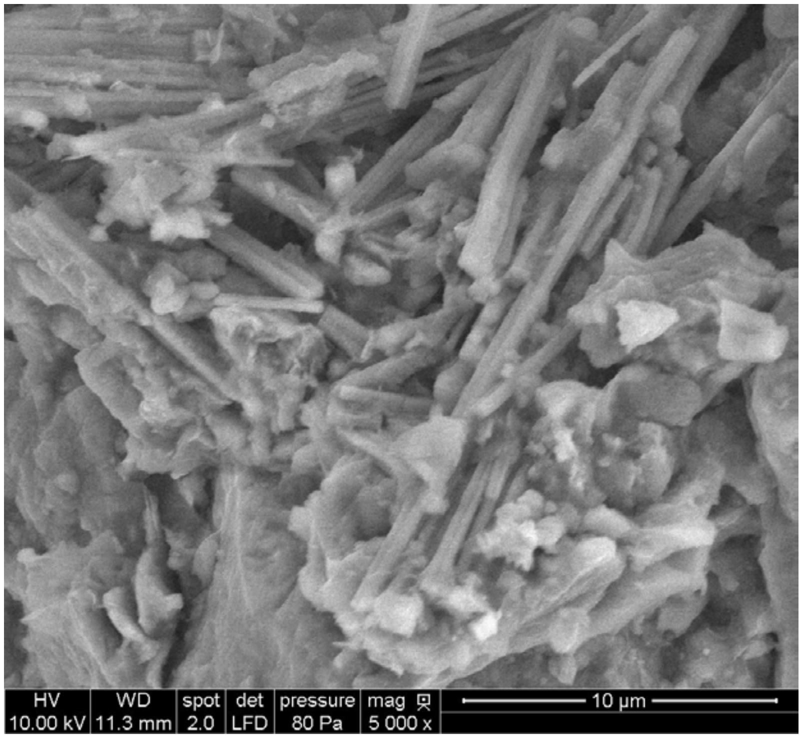

Figure 153. SEM image of natural subgrade (5000 ×) – US 183

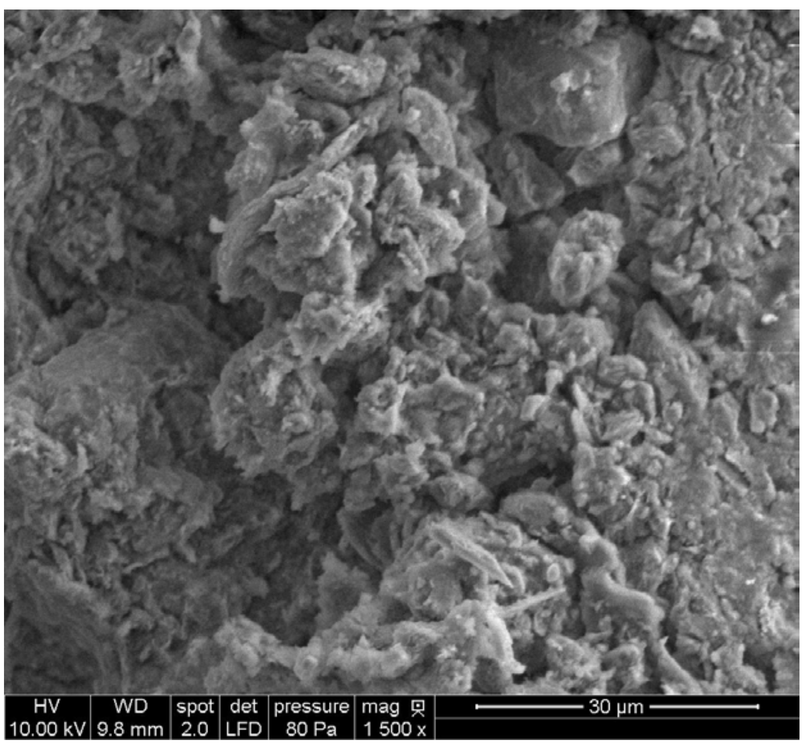

Figure 154. SEM image of stabilized subgrade (1500 ×) – US 183

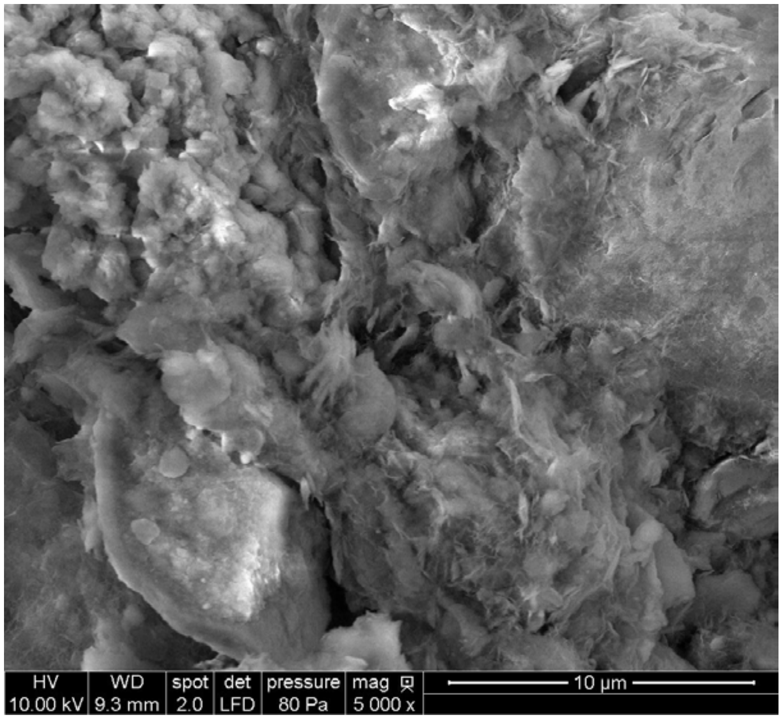

Figure 155. SEM image of stabilized subgrade (5000 ×) – US 183

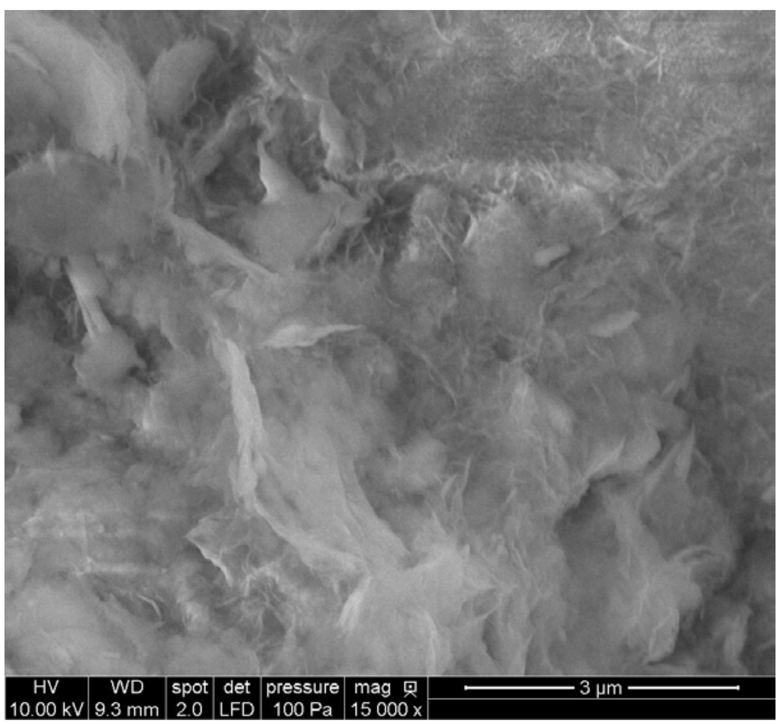

Figure 156. SEM image of stabilized subgrade (15000 ×) – US 183

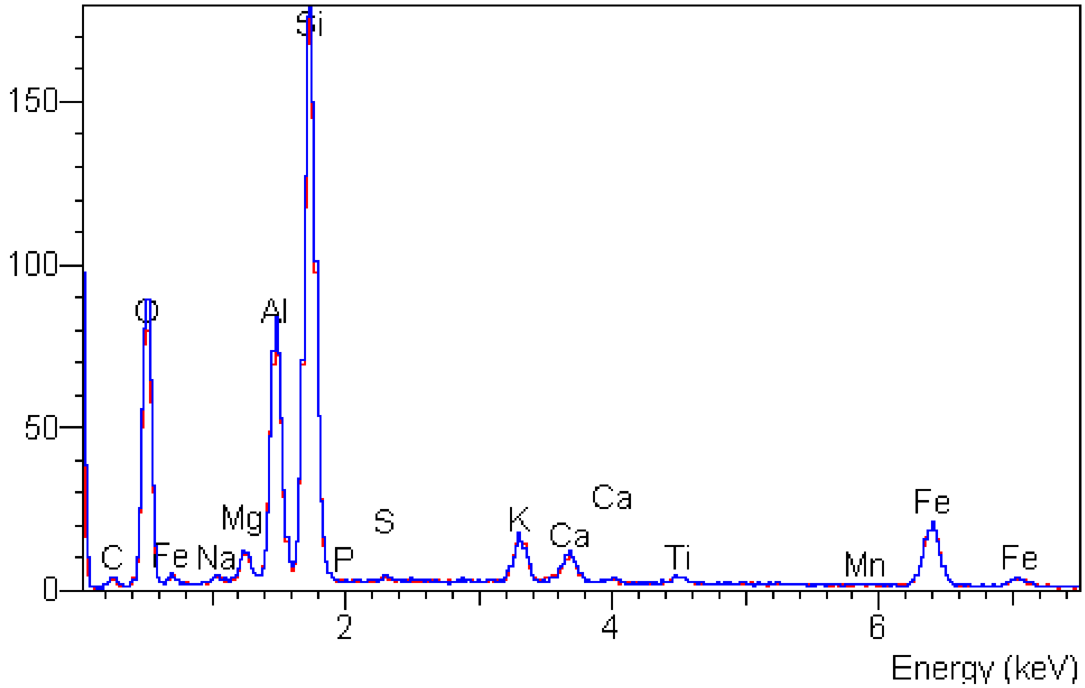

Figure 157. EDS intensity counts for stabilized subgrade sample (red line 150x; blue line 25x) – SH 99

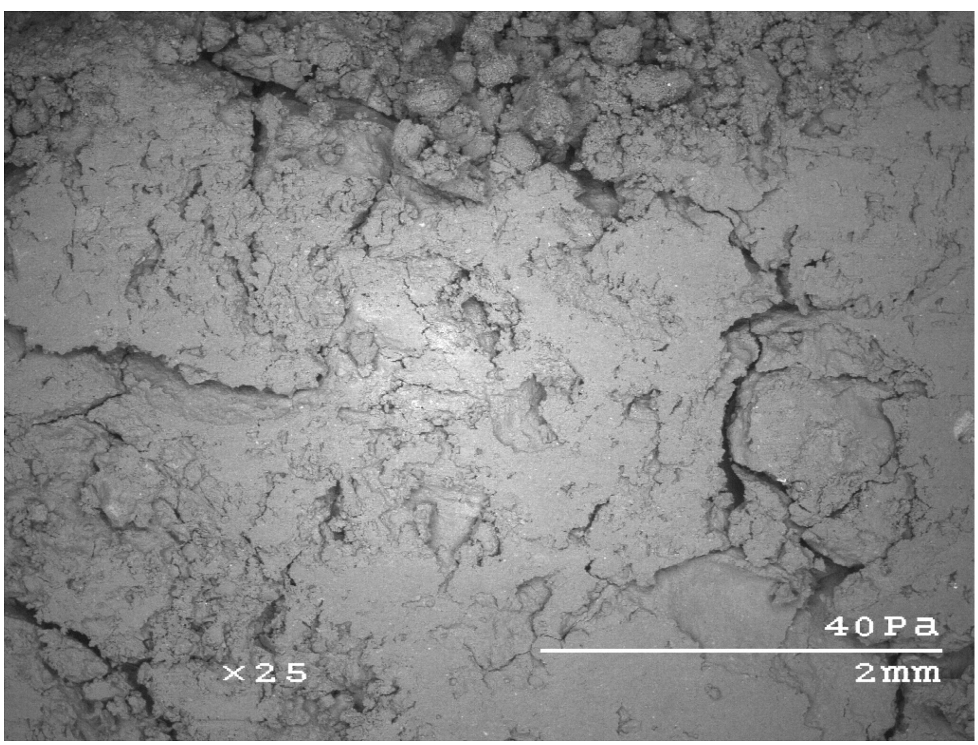

Figure 158. SEM image of stabilized subgrade (25 ×) in area a – SH 99

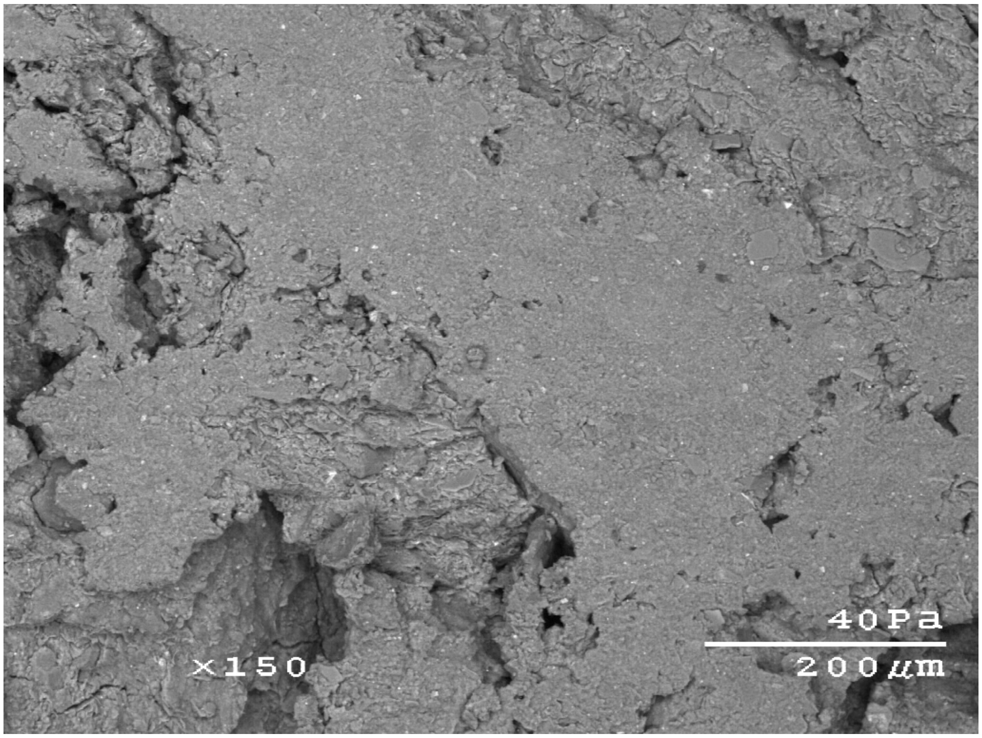

Figure 159. SEM image of stabilized subgrade (150 ×) in area a – SH 99

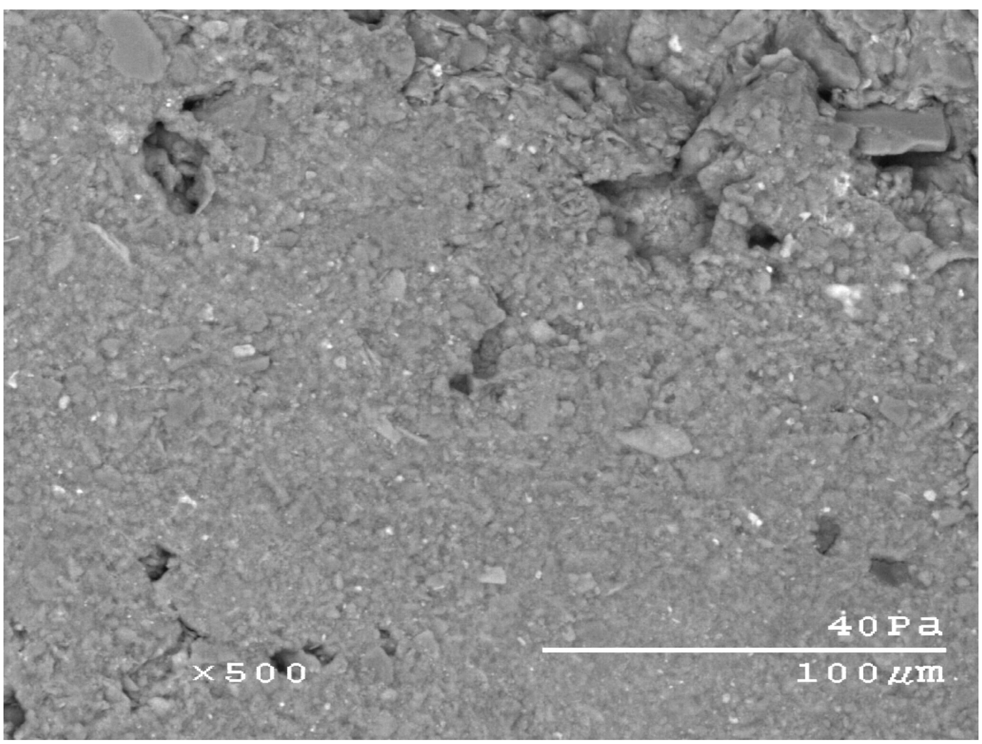

Figure 160. SEM image of stabilized subgrade (500 ×) in area a – SH 99

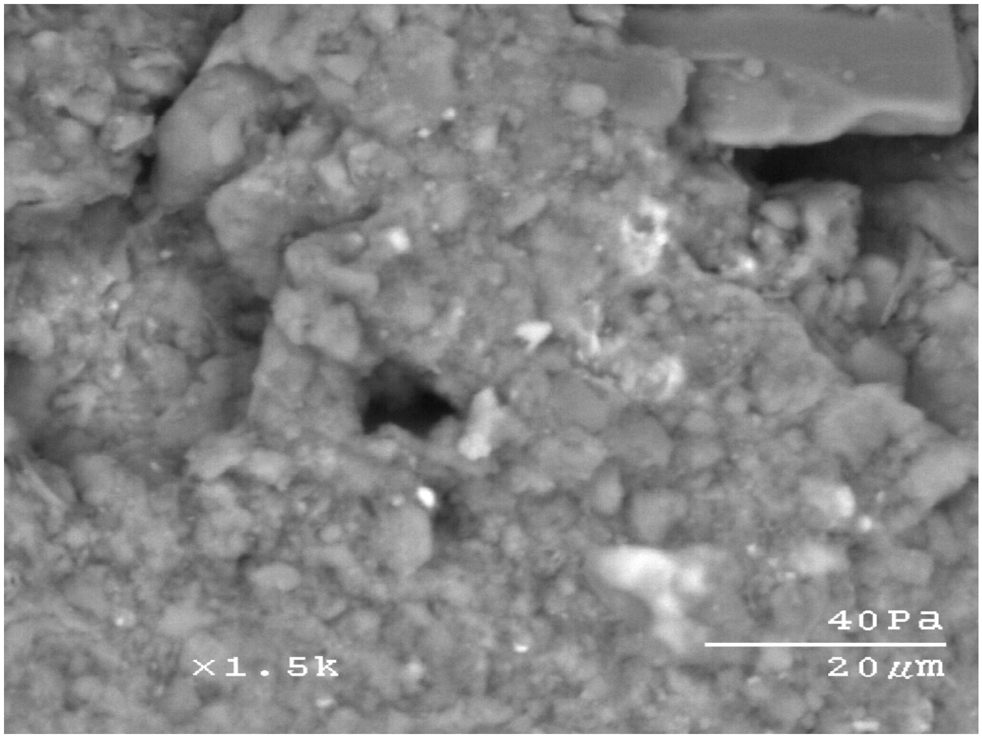

Figure 161. SEM image of stabilized subgrade (1500 ×) in area a – SH 99

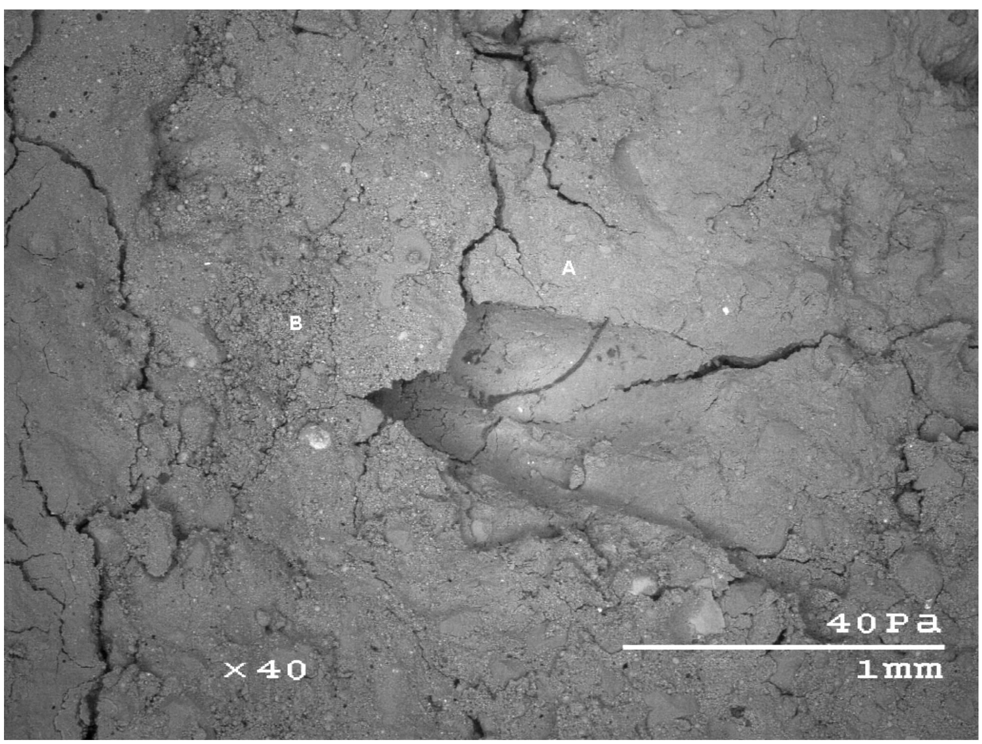

Figure 162. SEM image of stabilized subgrade (40 ×) in area b – SH 99

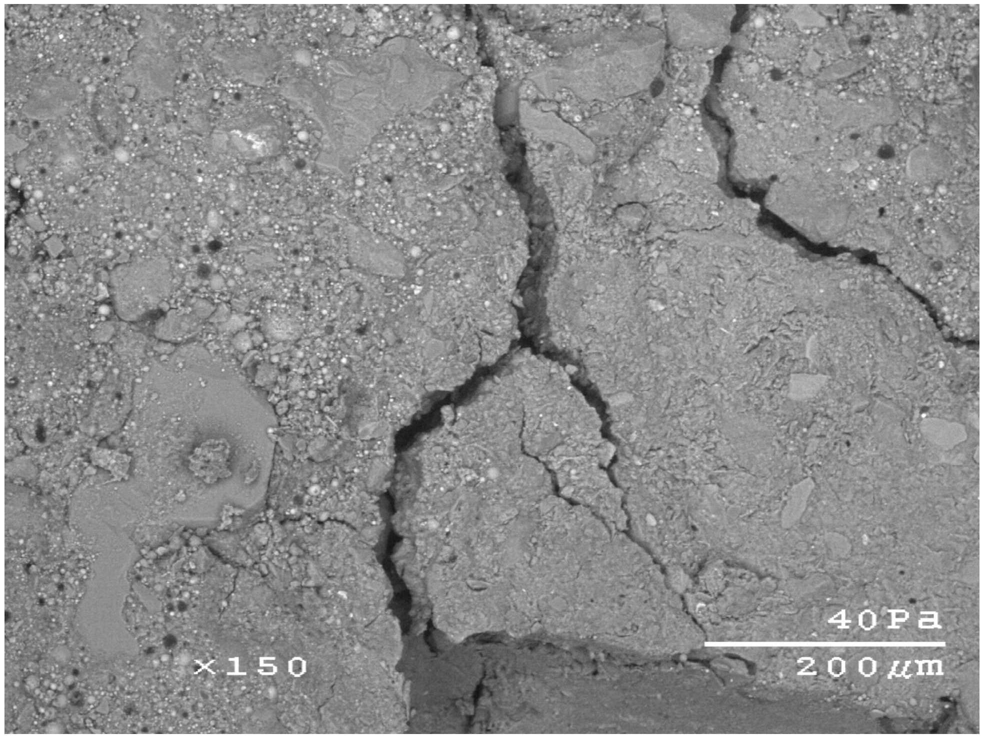

Figure 163. SEM image of stabilized subgrade (150 ×) in area b – SH 99

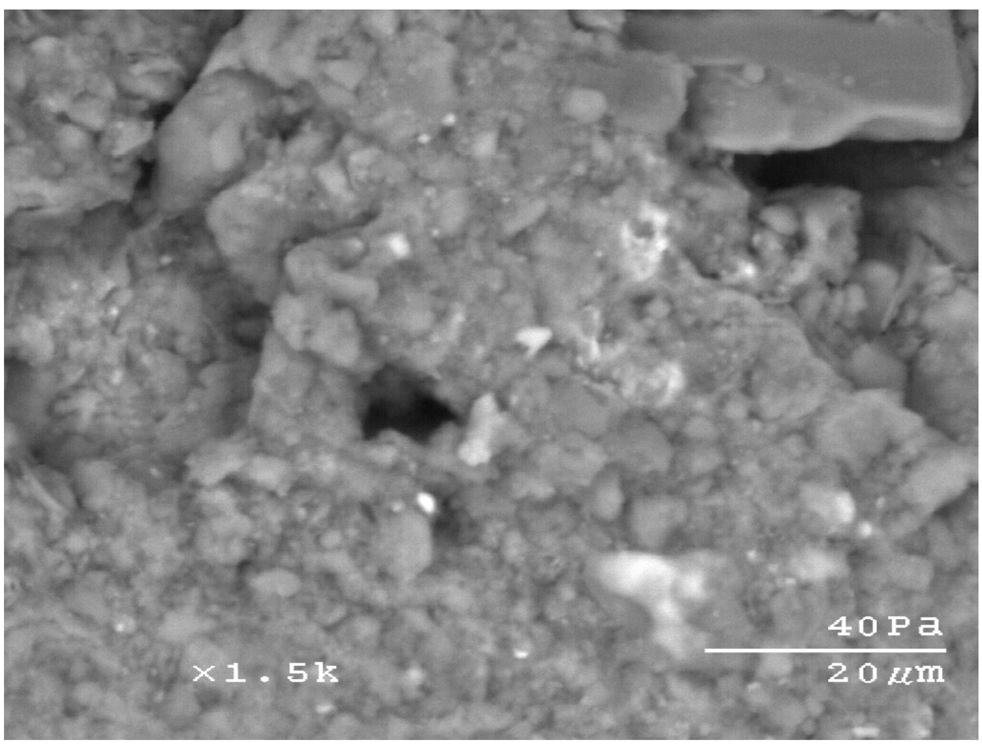

Figure 164. SEM image of stabilized subgrade (1500 ×) in area b – SH 99

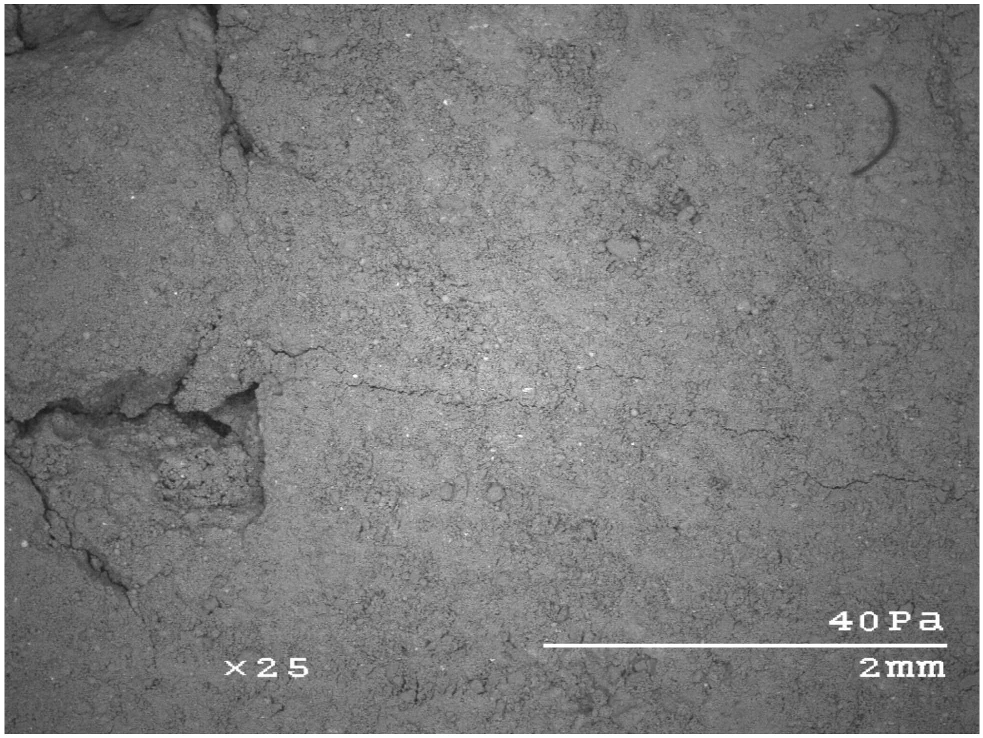

Figure 165. SEM image of stabilized subgrade (25 ×) -US 59

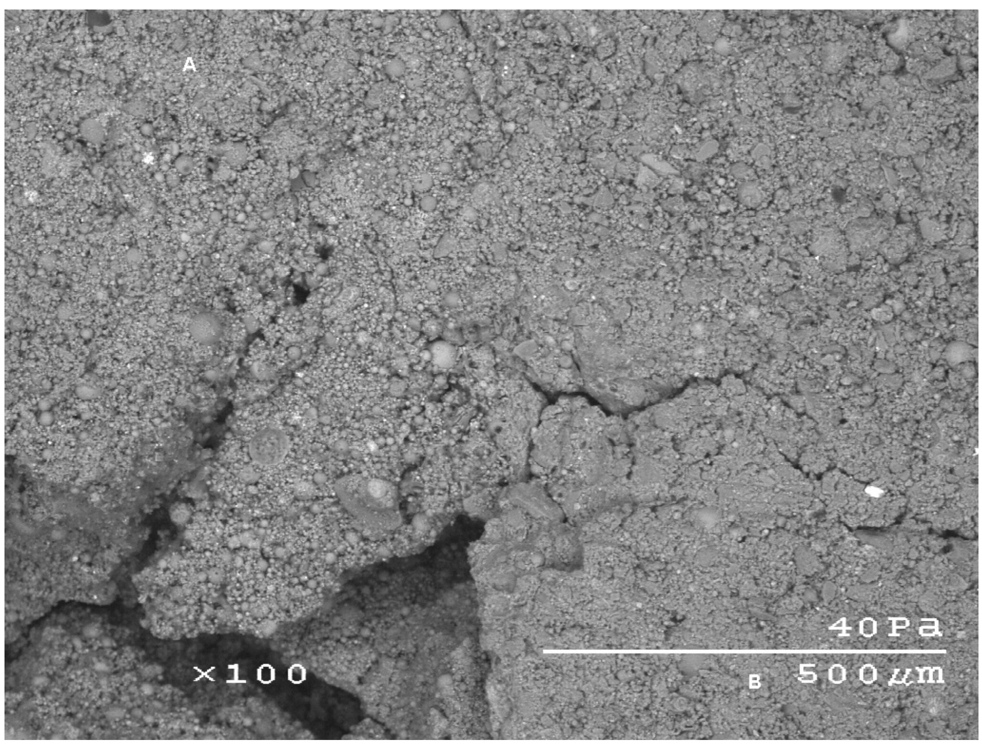

Figure 166. SEM image of stabilized subgrade (100 ×) – US 59

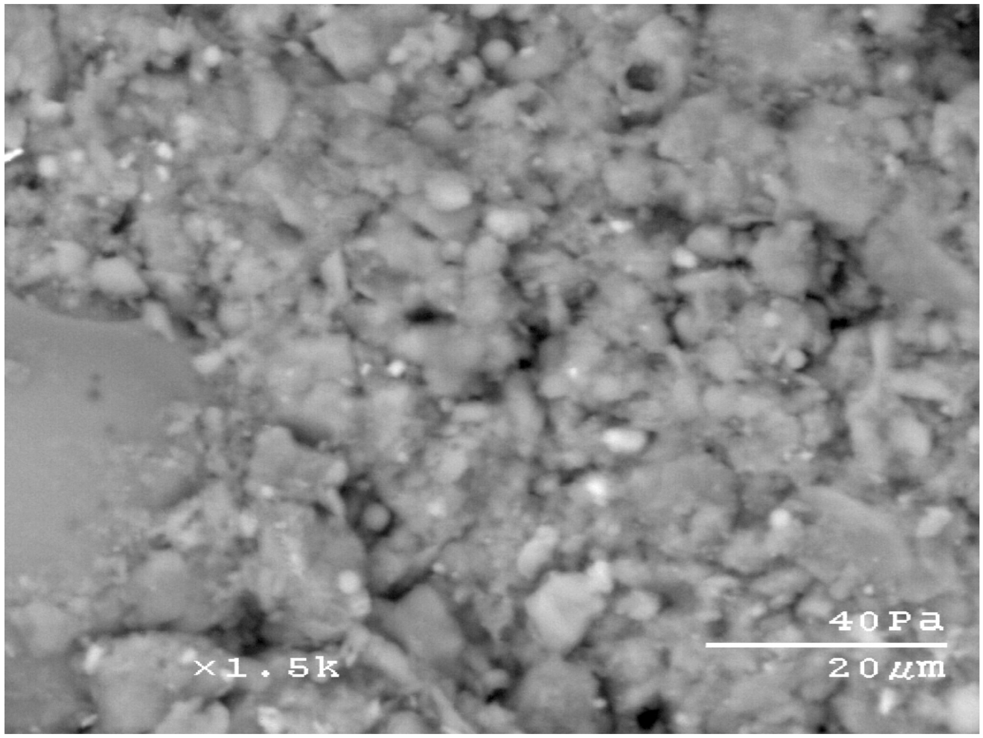

Figure 167. SEM image of stabilized subgrade (1500 ×) – US 59

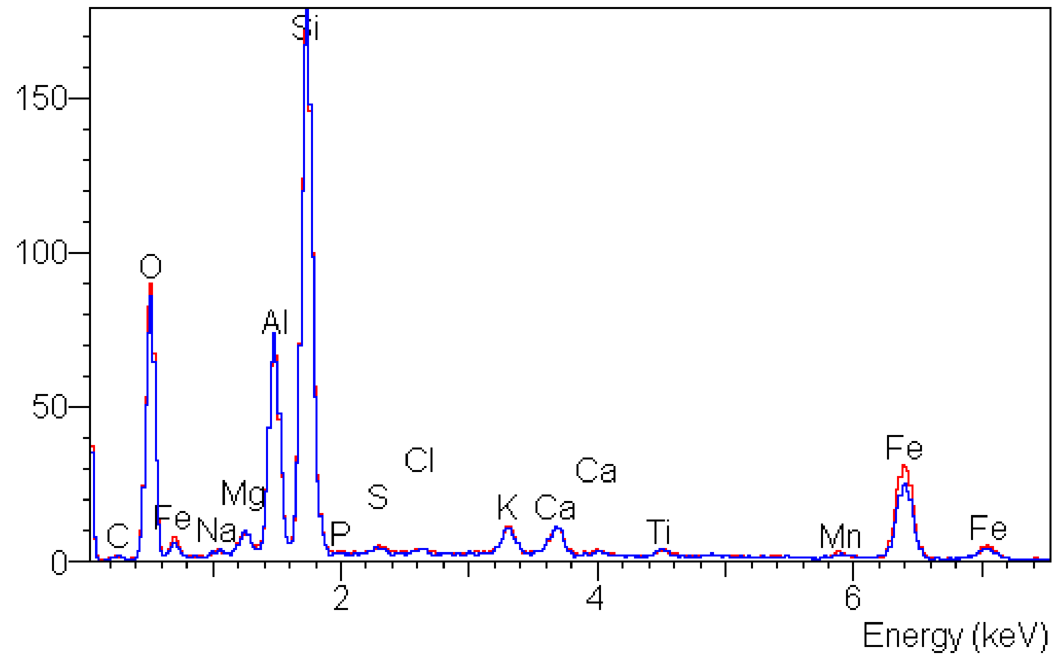

Figure 168. EDS intensity counts for stabilized subgrade sample (red line: 1500×, blue line: 500 ×) – US 75 NB

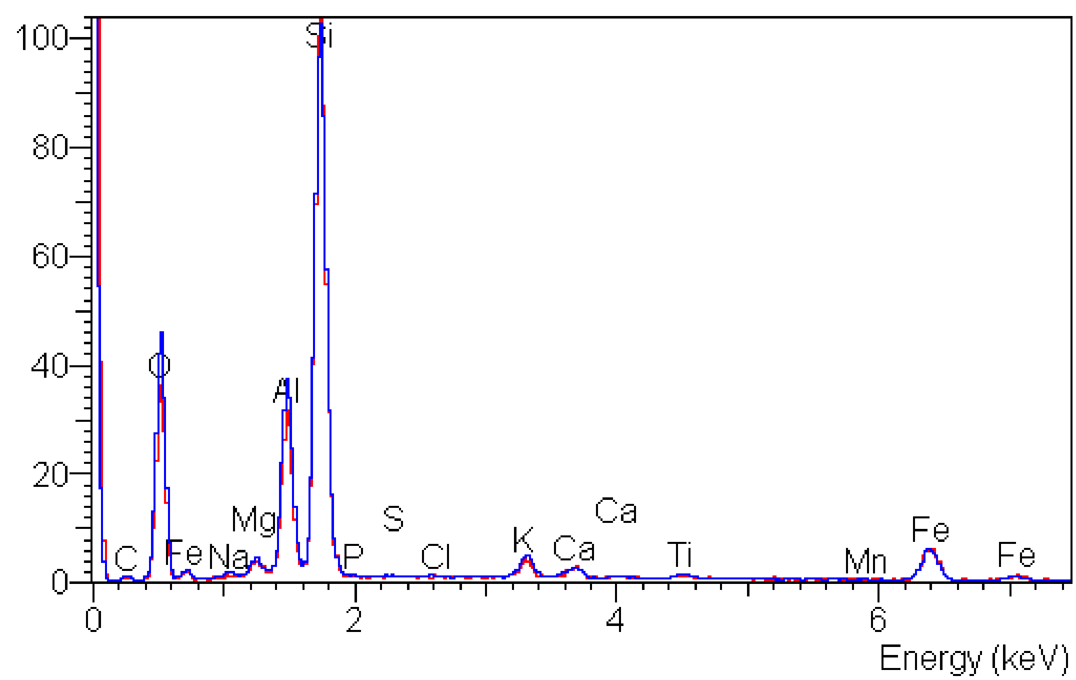

Figure 169. EDS intensity counts for stabilized subgrade sample (red line: 1500×, blue line: 150 ×) – US 75 NB

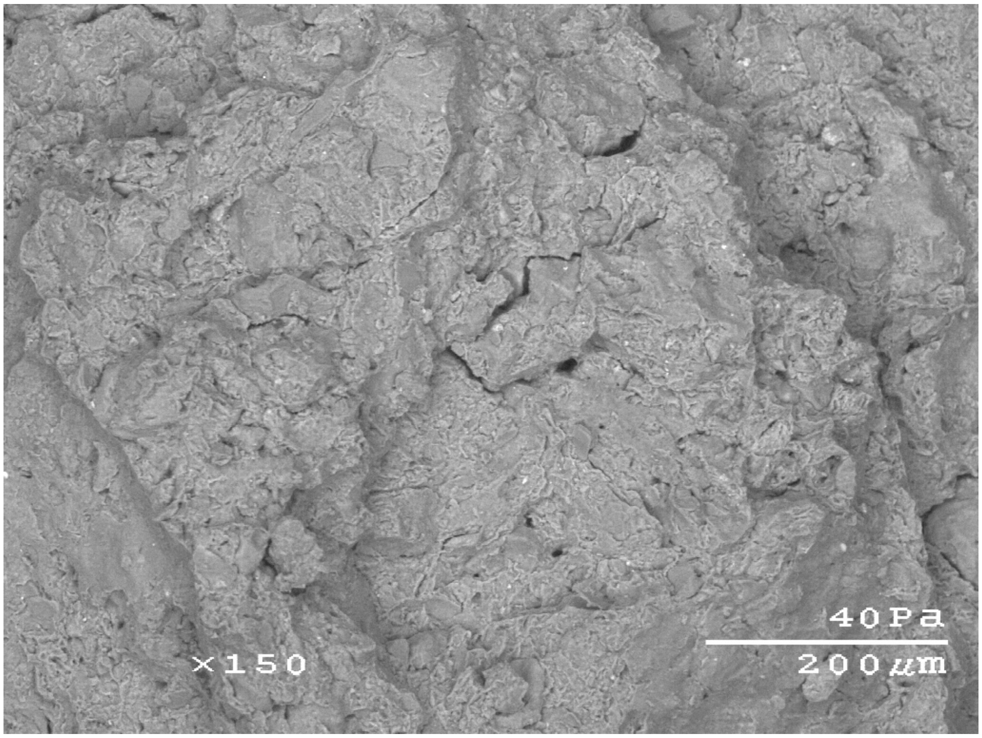

Figure 170. SEM image of natural subgrade in area b (150×) – US 75 SB

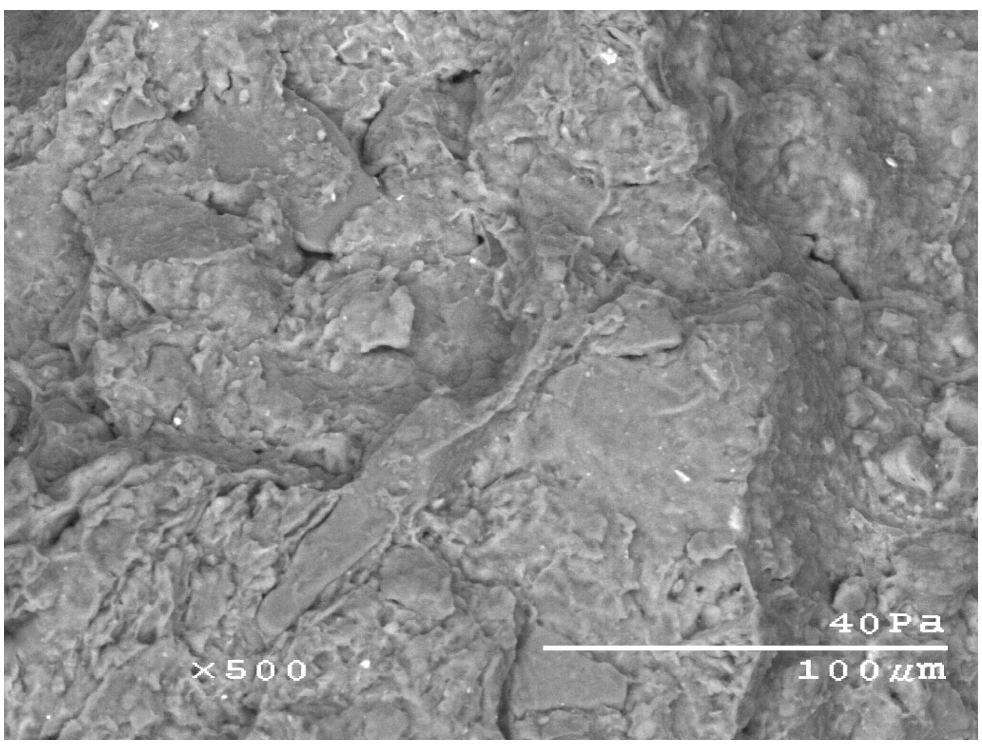

Figure 171. SEM image of natural subgrade in area b (500×) – US 75 SB

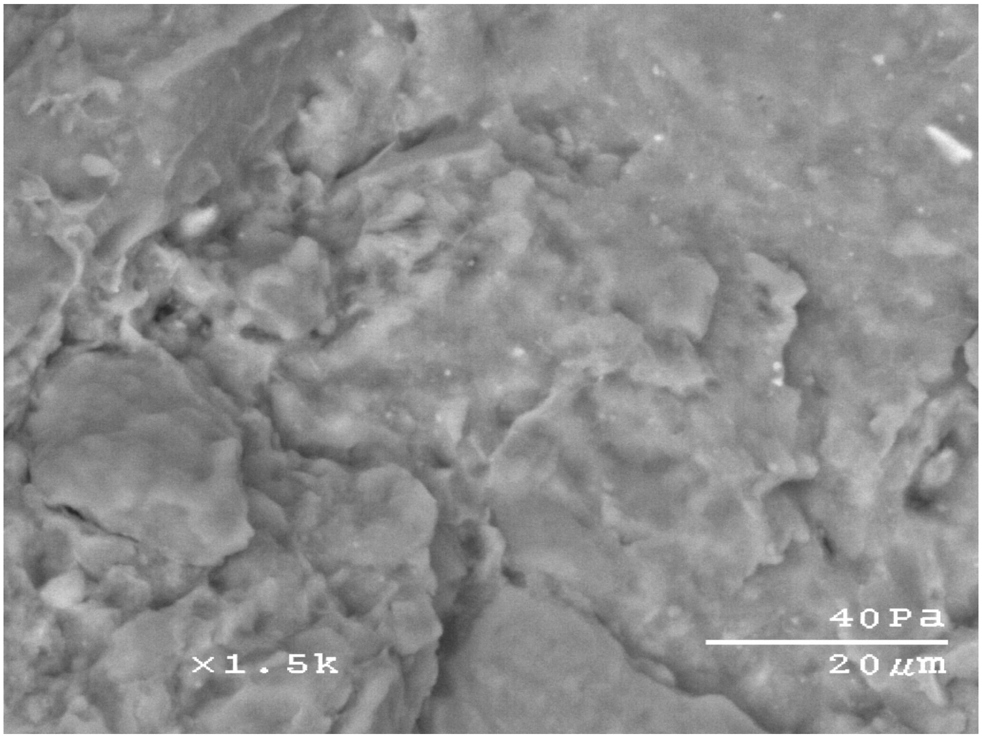

Figure 172. SEM image of natural subgrade in area b (1500×) – US 75 SB

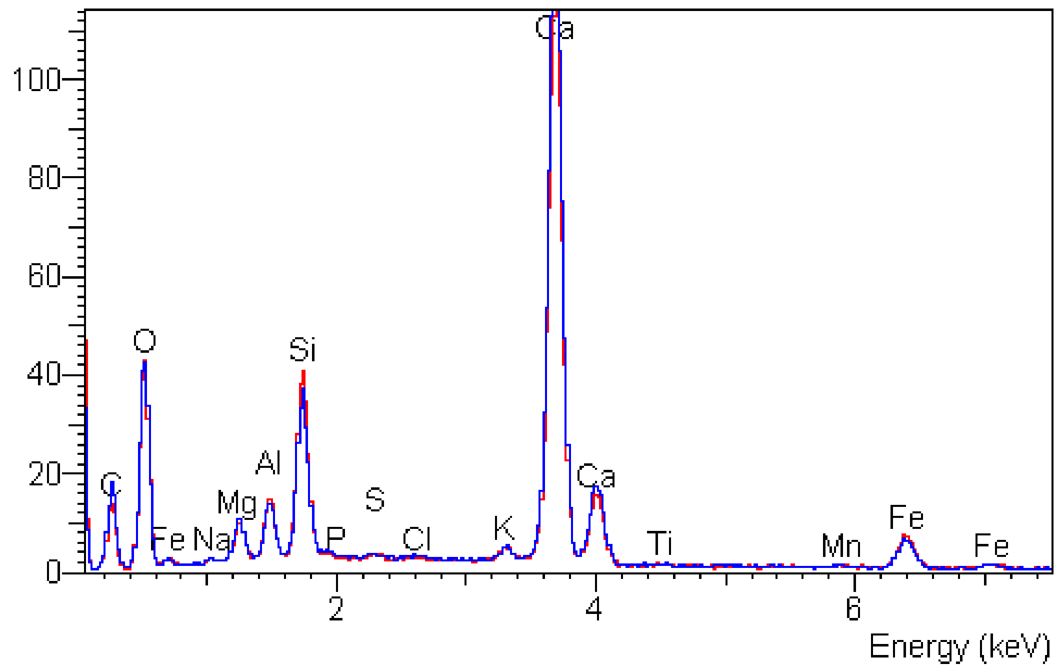

Figure 173. EDS intensity counts for stabilized subgrade sample (red line: 30×, blue line: 150 ×) – K 7

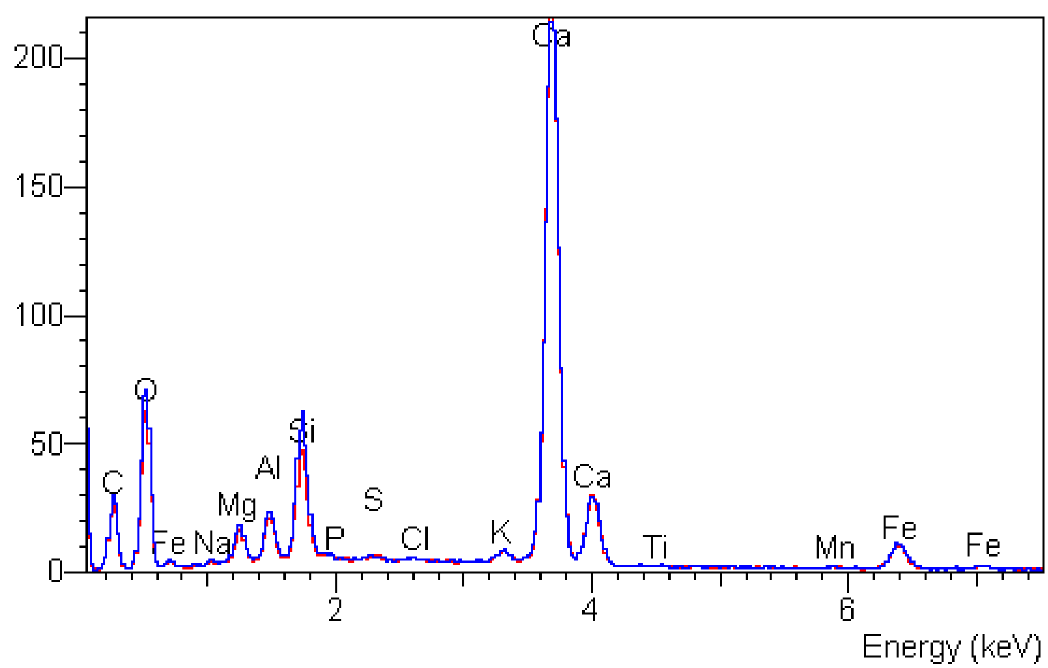

Figure 174. EDS intensity counts for stabilized subgrade sample (red line: 500×, blue line: 150 ×) – K 7

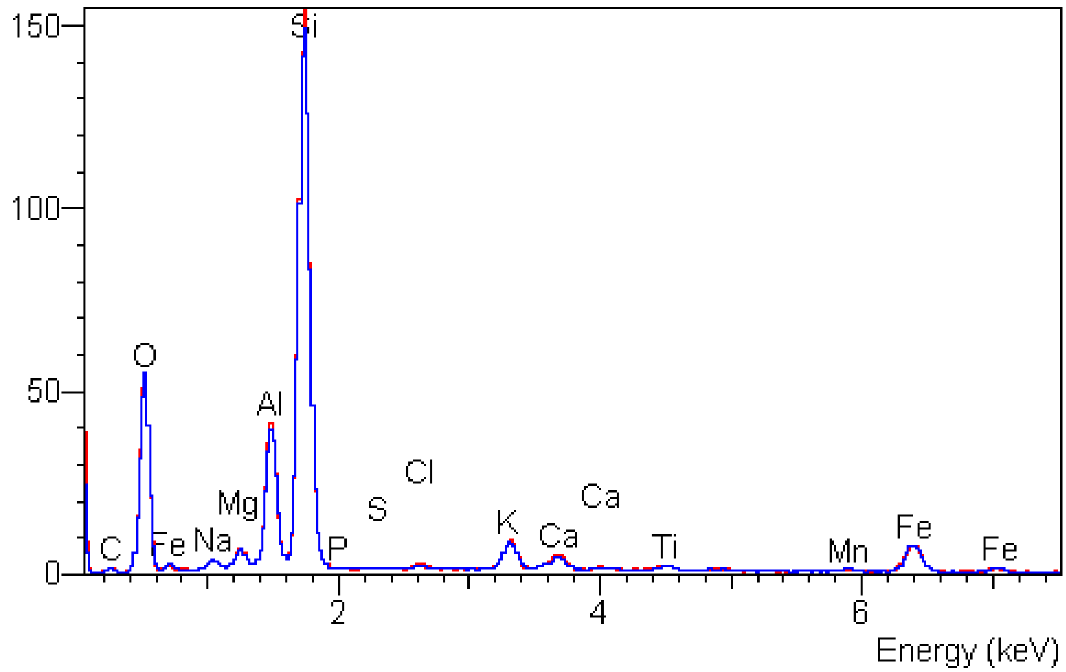

Figure 175. EDS intensity counts for natural subgrade sample (red line: 30×, blue line: 150 ×) – K 7

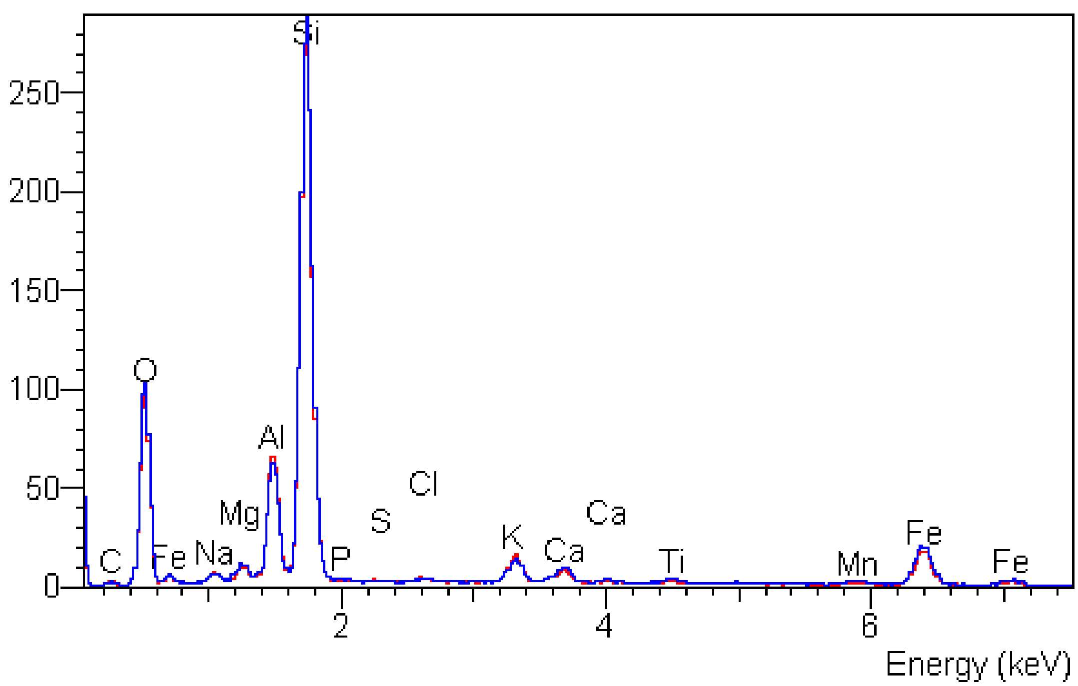

Figure 176. EDS intensity counts for natural subgrade sample (red line: 1500×; blue line: 500 ×) – K 7

APPENDIX E: ASSUMPTION FOR FWD ANALYSIS

Table 46. Assumptions for E_{FWD} analysis – SH 121

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thi.
PT	psi	psi	psi	in.	psi	psi	psi	in.	psi	psi	psi	in.	in.
1	1500000	60000	6000000	2	150000	10000	600000	8	60000	10000	500000	12	400
2	1500000	60000	6000000	2	150000	10000	600000	8	60000	10000	500000	10	400
3	1500000	60000	6000000	2	150000	10000	600000	8	60000	10000	500000	10	400
4	1000000	60000	6000000	2	100000	10000	600000	8	40000	10000	500000	8	340
5	1000000	60000	6000000	2	100000	10000	600000	8	40000	10000	500000	8	340
6	1000000	60000	6000000	2	100000	10000	600000	8	40000	10000	500000	10	400
7	1000000	60000	6000000	2	100000	10000	600000	8	90000	10000	500000	8	240
8	1500000	60000	6000000	2	150000	10000	600000	8	60000	10000	500000	14	400
9	1000000	60000	6000000	3	40000	10000	600000	8	90000	10000	500000	8	500
10	1000000	60000	6000000	3	40000	10000	600000	8	90000	10000	500000	8	175
11	1000000	60000	6000000	3	40000	10000	600000	8	90000	10000	500000	8	480
12	1000000	60000	6000000	3	40000	10000	600000	8	90000	10000	500000	8	480
13	600000	60000	6000000	2	40000	10000	600000	8	60000	10000	500000	8	380
14	600000	60000	6000000	2	40000	10000	600000	8	60000	10000	500000	8	380

Table 47. Assumptions for E_{FWD} analysis – FM 1709

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi	Thi
PT	psi	psi	psi	in.	psi	psi	psi	in.	psi	psi	psi	in.	in.
1	100000	50000	3000000	6.5	50000	10000	500000	7.5	30000	10000	80000	6	120
2	100000	50000	3000000	6.5	50000	10000	500000	7.5	30000	10000	80000	6	350
3	100000	50000	3000000	6.5	50000	10000	500000	7.5	30000	10000	80000	6	350
4	100000	50000	3000000	6.5	50000	10000	500000	7.5	30000	10000	80000	6	350
5	100000	50000	3000000	6.5	50000	10000	1000000	7.5	30000	10000	200000	6	350
6	100000	50000	3000000	6.5	50000	10000	5000000	7.5	30000	10000	800000	6	150
7	100000	50000	3000000	6.5	50000	10000	1000000	7.5	40000	15000	300000	6	400
8	100000	50000	3000000	6.5	50000	10000	1000000	7	20000	15000	300000	4	120

Table 48. Assumptions for E_{FWD} analysis – US 287

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Nat. Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thi.
PT	psi	psi	psi	in	psi	psi	psi	in	psi	psi	psi	in	in
1	1000000	500000	5000000	4	10000	1000	300000	8	60000	10000	200000	14	180
2	40000	200000	5000000	4	1000	1000	300000	11	60000	10000	200000	14	260
3	800000	100000	5000000	4	80000	1000	300000	8	80000	10000	500000	14	300
4	800000	100000	5000000	4	80000	1000	300000	11	80000	10000	500000	14	280
5	800000	100000	5000000	4	80000	1000	300000	11	80000	10000	500000	14	200
6	500000	10000	5000000	4	100000	1000	300000	8	120000	10000	500000	14	260
7	500000	10000	5000000	4	100000	1000	300000	8	120000	10000	500000	14	300
8	500000	10000	5000000	4	100000	1000	300000	8	120000	10000	500000	18	250
9	500000	10000	5000000	4	100000	1000	300000	11	120000	10000	500000	14	250
10	500000	10000	5000000	4	100000	1000	300000	11	120000	10000	500000	18	250
11	800000	200000	5000000	4	60000	1000	300000	11	50000	10000	200000	14	250
12	800000	200000	5000000	4	60000	1000	300000	11	50000	10000	200000	14	300
13	500000	10000	5000000	4	100000	1000	300000	11	120000	10000	500000	16	350
14	500000	10000	5000000	2	100000	1000	300000	11	120000	10000	500000	16	350
15	800000	200000	5000000	4	80000	1000	300000	11	50000	10000	200000	14	350
16	800000	200000	5000000	4	80000	1000	300000	11	50000	10000	200000	14	310
17	800000	200000	5000000	4	80000	1000	300000	11	50000	10000	200000	14	310
18	800000	200000	5000000	4	80000	1000	300000	11	50000	10000	200000	14	310
19	800000	200000	5000000	4	80000	1000	300000	6	50000	10000	200000	14	310

Table 49. Assumptions for E_{FWD} analysis – US 183

	ACC pavement (Layer 1)				Stabilized Subgrade (Layer 2)				Natural Subgrade
	Seed	Minimum	Maxium	Thickness	Seed	Minimum	Maximum	Thickness	Thickness
PT	psi	psi	psi	in.	psi	psi	psi	in.	in.
1	850000	300000	2000000	12	390000	10000	700000	8.7	240
2	750000	300000	2000000	12	160000	10000	700000	8.5	240
3	1200000	600000	5000000	12	220000	10000	3000000	8.4	240
4	1200000	600000	5000000	12	120000	10000	3000000	8.3	240
5	650000	300000	3000000	12	300000	10000	380000	8.1	240
6	700000	300000	3000000	12	240000	10000	380000	8	240
7	700000	300000	3000000	12	240000	10000	380000	7.8	240
8	700000	300000	3000000	12	240000	10000	380000	7.7	240
9	460000	300000	9000000	12	120000	10000	280000	3.4	240
10	1000000	100000	3000000	12	260000	50000	580000	8	240
11	1000000	100000	3000000	12	260000	50000	580000	8	240
12	700000	100000	3000000	12	240000	50000	580000	6	240
13	700000	100000	3000000	12	340000	50000	580000	8	240
14	700000	100000	3000000	12	340000	50000	580000	8	240
15	700000	100000	3000000	12	340000	50000	580000	8	240
16	700000	100000	3000000	12	340000	50000	580000	8	240
17	700000	100000	3000000	12	200000	50000	580000	8	240
18	700000	100000	3000000	12	230000	50000	580000	6	240
19	800000	100000	3000000	12	220000	50000	580000	8	240
20	900000	100000	3000000	12	220000	50000	580000	8	240
21	600000	100000	3000000	12	220000	50000	580000	8	240
22	850000	100000	3000000	12	340000	50000	580000	8	240
23	900000	100000	3000000	12	280000	50000	580000	8	240
24	400000	100000	10000000	12	330000	50000	580000	8	240
25	1000000	100000	3000000	12	270000	50000	580000	8	240

Table 50. Assumptions for E_{FWD} analysis – SH 99

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Subgrade
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thickness
PT	psi	psi	psi	in	psi	psi	psi	In.	psi	psi	psi	in	in
1	3000000	100000	5000000	10	30000	1000	250000	4	50000	10000	100000	11	210
2	3000000	100000	5000000	10	10000	2000	250000	6	50000	10000	100000	8	300
3	3000000	100000	5000000	10	10000	2000	250000	6	50000	10000	100000	10	300
4	3000000	100000	5000000	10	10000	2000	250000	6	50000	10000	100000	8	300
5	3000000	100000	5000000	10	10000	2000	250000	6	50000	10000	100000	8	300
6	3000000	100000	5000000	10	10000	2000	250000	6	50000	10000	100000	8	300
7	1000000	100000	5000000	10	10000	2000	550000	6	50000	10000	100000	8	300
8	3000000	100000	5000000	10	40000	10000	550000	8	50000	10000	100000	12	280
9	3000000	100000	5000000	10	10000	2000	550000	6	50000	10000	100000	8	280
10	3000000	100000	5000000	10	10000	2000	550000	6	50000	10000	100000	8	340
11	3000000	100000	5000000	10	100000	10000	550000	6	50000	10000	100000	8	340
12	3000000	100000	5000000	8	40000	2000	550000	6	50000	10000	100000	10	400
13	3000000	100000	5000000	8	40000	2000	550000	6	50000	10000	100000	10	340
14	3000000	100000	5000000	10	40000	2000	550000	6	50000	10000	100000	8	300
15	3000000	100000	5000000	10	40000	2000	550000	6	50000	10000	100000	8	300
16	2500000	100000	5000000	8	10000	2000	550000	5	80000	10000	100000	7	240
17	2500000	100000	5000000	8	10000	2000	550000	5	80000	10000	300000	7	360
18	2500000	100000	5000000	9	10000	2000	550000	6	80000	10000	300000	8	360
19	2500000	100000	5000000	10	10000	2000	550000	6	80000	10000	300000	8	300
20	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	280
21	900000	100000	5000000	9	10000	2000	550000	6	80000	10000	300000	8	300
22	900000	100000	5000000	10	10000	2000	550000	6	80000	10000	300000	8	340
23	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	340
24	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
25	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
26	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
27	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360

Table 51. Assumptions for E_{FWD} analysis – SH 99 (con't)

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Subgrade
28	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
29	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
30	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
31	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
32	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
33	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
34	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
35	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
36	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
37	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
38	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
39	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
40	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
41	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
42	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
43	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	100000	10	340
44	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360
45	900000	100000	5000000	10	10000	2000	550000	6	50000	10000	300000	8	360

Table 52. Assumptions for E_{FWD} analysis – US 59

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Nat. Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thi.
PT	psi	psi	psi	in.	psi	psi	psi	in.	psi	psi	psi	in.	in.
1	800000	200000	3000000	10	50000	10000	1000000	10	100000	30000	200000	8	240
2	750000	200000	2000000	10	20000	4000	500000	10	100000	10000	800000	8	240
3	550000	100000	5000000	10	30000	10000	200000	10	80000	10000	300000	8	240
4	450000	200000	2000000	10	20000	4000	500000	10	70000	10000	800000	8	240
5	850000	100000	5000000	10	20000	10000	200000	10	90000	10000	300000	8	300
6	800000	200000	2000000	10	30000	4000	500000	10	120000	10000	800000	8	240
7	850000	100000	5000000	10	20000	10000	200000	10	90000	10000	300000	8	300
8	800000	200000	2000000	10	20000	4000	500000	10	90000	10000	800000	8	240
9	800000	200000	2000000	10	20000	4000	500000	10	90000	10000	800000	8	240
10	800000	100000	5000000	10	20000	4000	90000	10	40000	10000	500000	12	120
11	800000	200000	3000000	10	20000	4000	500000	10	90000	30000	200000	8	140
12	800000	100000	5000000	10	30000	10000	500000	10	90000	10000	300000	8.3	95
13	800000	100000	5000000	10	40000	10000	500000	10	90000	10000	300000	8.6	110
14	700000	100000	5000000	10	20000	4000	100000	6	80000	10000	300000	6	160
15	800000	200000	2000000	10	40000	4000	300000	10	50000	10000	300000	8	110
16	800000	100000	5000000	10	40000	10000	500000	8	80000	10000	750000	8	110
17	700000	400000	6000000	10	30000	10000	80000	10	100000	50000	800000	8	80
18	600000	100000	5000000	10	30000	10000	200000	8	80000	10000	200000	10	110
19	800000	100000	5000000	10	30000	10000	500000	10	80000	10000	750000	9.5	80
20	700000	200000	2000000	10	35000	10000	500000	10	200000	40000	500000	8	100
21	800000	100000	5000000	10	30000	10000	500000	10	80000	10000	750000	9	180
22	700000	100000	2000000	12	20000	10000	200000	8	80000	10000	200000	6	100
23	700000	400000	6000000	10	20000	4000	80000	10	110000	40000	250000	8	240
24	700000	100000	5000000	12	20000	4000	200000	8	80000	10000	200000	10	110
25	560000	400000	6000000	10	20000	4000	80000	10	95000	40000	450000	8	240
26	560000	400000	6000000	10	20000	4000	80000	10	95000	40000	450000	8	240
27	560000	400000	6000000	10	50000	4000	80000	10	95000	40000	450000	8	240
28	560000	400000	6000000	10	40000	4000	80000	10	95000	40000	450000	8	240

Table 53. Assumptions for E_{FWD} analysis – US 59 (con't)

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Nat. Sub.
29	560000	400000	6000000	10	40000	4000	80000	10	95000	40000	450000	8	240
30	560000	400000	6000000	10	30000	4000	80000	10	95000	40000	450000	8	240
31	560000	400000	6000000	10	20000	4000	80000	10	95000	40000	450000	8	240

Table 54. Assumptions for E_{FWD} analysis – US 75 SB

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thi.
PT	psi	psi	psi	in	psi	psi	psi	in	psi	psi	psi	in	in
1	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	210
2	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	210
3	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	210
4	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
5	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
6	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
7	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
8	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
9	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
10	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
11	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
12	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
13	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
14	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
15	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
16	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
17	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
18	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
19	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
20	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
21	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
22	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	180
23	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
24	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
25	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
26	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
27	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150

Table 55. Assumptions for E_{FWD} analysis – US 75 SB (con't)

	ACC pavement (Layer 1)				Aggregate Base (Layer 2)				Stabilized Subgrade (Layer 3)				Natural Sub.
28	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
29	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
30	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	150
31	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	160
32	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	160
33	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	160
34	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
35	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
36	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
37	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
38	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
39	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
40	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	260
41	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
42	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
43	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	250
44	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
45	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
46	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	200
47	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	260
48	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	260
49	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	260
50	1000000	500000	5000000	14	10000	1000	250000	2	80000	10000	300000	4	260

Table 56. Assumptions for E_{FWD} analysis – K 7

	ACC pavement (Layer 1)				Stabilized Subgrade (Layer 2)				Natural Sub.
	Seed	Minimum	Maximum	Thi.	Seed	Minimum	Maximum	Thi.	Thi.
PT	psi	psi	psi	in.	psi	psi	psi	in.	in.
1	1000000	100000	5000000	8	100000	10000	200000	10	290
2	1000000	100000	5000000	8	100000	10000	200000	10	290
3	1000000	100000	5000000	8	100000	10000	200000	10	290
4	1000000	100000	5000000	8	100000	10000	200000	10	290
5	1000000	100000	5000000	8	100000	10000	200000	10	390
6	1000000	100000	5000000	8	100000	10000	200000	10	390
7	1000000	100000	5000000	8	100000	10000	200000	10	390
8	1000000	100000	5000000	8	100000	10000	200000	10	390
9	1000000	100000	5000000	8	100000	10000	200000	10	390
10	1000000	100000	5000000	8	100000	10000	200000	10	390
11	1000000	100000	5000000	8	100000	10000	200000	10	390
12	1000000	100000	5000000	8	100000	10000	200000	10	390
13	1000000	100000	5000000	8	100000	10000	200000	10	390
14	1000000	100000	5000000	8	100000	10000	200000	10	390
15	1000000	100000	5000000	8	100000	10000	200000	10	390
16	1000000	100000	5000000	8	100000	10000	200000	10	390
17	1000000	100000	5000000	8	100000	10000	200000	10	390
18	1000000	100000	5000000	8	100000	10000	200000	10	390
19	1000000	100000	5000000	8	100000	10000	200000	10	390
20	1000000	100000	5000000	8	100000	10000	200000	10	390
21	1000000	100000	5000000	8	100000	10000	200000	10	390
22	1000000	100000	5000000	8	100000	10000	200000	10	390
23	1000000	100000	5000000	9	100000	10000	200000	10	390
24	1000000	100000	5000000	8	100000	10000	200000	10	390
25	1000000	100000	5000000	8	100000	10000	200000	10	390

Table 57. Assumptions for E_{FWD} analysis – K 7 (con't)

	ACC pavement (Layer 1)				Stabilized Subgrade (Layer 2)				Natural Sub.
26	1000000	100000	5000000	8	100000	10000	200000	10	390
27	1000000	100000	5000000	8	100000	10000	200000	10	390
28	1000000	100000	5000000	8	100000	10000	200000	10	390
29	1000000	100000	5000000	7	50000	10000	200000	10	200
30	1000000	100000	5000000	9	100000	10000	200000	10	490
31	1000000	100000	5000000	9	100000	10000	200000	10	490

APPENDIX F: SUMMARY OF FIELD TEST RESULTS

Table 58. Summary of test results from in-situ testing – SH 121

	Flex Base	Stabilized Subgrade					Natural Sub.	FWD Def.
	E_{LWD}	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	E_{FWD}	D_0
PT	MPa	%	MPa	MPa	MPa	MPa	MPa	mm
1	—	—	1112	—	—	—	262	0.31
2	—	—	1313	—	—	—	198	0.34
3	—	—	1298	—	—	—	218	0.28
4	83	119	1620	51	140	360	169	0.35
5	—	—	2022	—	—	—	265	0.31
6	—	—	1124	—	—	—	204	0.42
7	140	—	297	87	282	338	152	0.63
8	—	—	2419	—	—	—	285	0.30
9	—	—	575	—	—	—	245	0.36
10	—	—	779	—	—	—	406	0.27
11	125	—	582	70	—	—	356	0.20
12	—	—	728	—	—	—	274	0.29
13	—	—	867	—	—	—	290	0.15
14	—	—	1077	—	—	—	340	0.30

Table 59. Summary of test results from in-situ testing – FM 1709

	Stabilized Subgrade						Natural Subgrade		FWD Def.
	CBR	E_{V1}	E_{V2}	E_{FWD}	E_{LWD}	Thi.	E_{FWD}	CBR	D_0
PT	%	MPa	MPa	MPa	MPa	mm	MPa	%	mm
1	53	129	184	129	240	100	74	24	0.63
2	—	—	—	385	—	—	121	—	0.45
3	—	—	—	237	—	—	103	—	0.49
4	—	—	—	287	—	—	186	—	0.32
5	—	—	—	609	—	—	112	—	0.50
6	—	—	—	171	—	—	95	—	0.50
7	—	—	—	550	—	—	120	—	0.34
8	—	—	—	802	—	—	208	—	0.36

Table 60. Summary of test results from in-situ testing – US 287

	Base		**Stabilized Subgrade**						**Natural Subgrade**		**FWD Def.**
	CBR	E_{LWD}	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	CBR	D_0
PT	MPa	MPa	%	MPa	MPa	MPa	MPa	mm	MPa	%	mm
1	—	—	—	125	—	—	—	—	84	—	0.50
2	—	—	—	346	—	—	—	—	108	—	0.50
3	—	—	—	1223	—	—	—	—	122	—	0.24
4	—	—	—	437	—	—	—	—	133	—	0.27
5	—	—	—	1330	—	—	—	—	120	—	0.28
6	—	—	—	2063	—	—	—	—	137	—	0.17
7	—	—	—	1327	—	—	—	—	131	—	0.27
8	—	—	—	1849	—	—	—	—	121	—	0.25
9	—	—	—	276	—	—	—	—	119	—	0.29
10	—	—	—	1643	—	—	—	—	131	—	0.23
11	—	—	—	375	—	—	—	—	94	—	0.39
12		107	150	842	65	150	235	400	99	22	0.38
13	—	—	—	1997	—	—	—	—	123	—	0.35
14	—	—	—	1807	—	—	—	—	106	—	0.25
15	60	—	—	570	—	—	—	—	99	—	0.27
16	133	—	175	353	—	—	—	—	105	—	0.51
17	—	—	—	372	—	—	—	—	93	—	0.46
18	—	—	—	183	—	—	—	—	88	—	0.36
19	—	—	—	481	—	—	—	—	95	—	0.52

Table 61. Summary of test results from in-situ testing – US 183

	Stabilized Subgrade						**Natural Subgrade**			**FWD Def.**	
	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	E_{LWD}	CBR	$D_{0\text{-Cor.}}$	D_0
PT	%	MPa	MPa	MPa	MPa	mm	MPa	MPa	%	mm	mm
1	214	2606	—	—	—	237	167	—	34	0.12	0.15
2	—	1089	—	—	—	—	139	—	—	0.15	0.20
3	—	1475	—	—	—	—	131	—	—	0.13	0.17
4	—	815	—	—	—	—	109	—	—	0.16	0.20
5	—	2076	—	—	—	—	140	—	—	0.15	0.20
6	—	1614	—	—	—	—	131	—	—	0.15	0.19
7	—	1610	—	—	—	—	140	—	—	0.15	0.19
8	147	1670	164	317	592	213	137	—	36	0.15	0.20
9	57	841	—	—	—	104	107	—	21	0.24	0.32
10	—	2000	—	—	—	—	120	—	—	0.17	0.22
11	—	1928	—	—	—	—	141	—	—	0.15	0.20
12	115	1706	—	—	—	149	139	—	23	0.17	0.22
13	—	2306	—	—	—	—	166	—	—	0.13	0.17
14	—	2347	—	—	—	—	150	—	—	0.13	0.18
15	—	2321	—	—	—	—	182	—	—	0.12	0.16
16	—	2399	—	—	—	—	160	—	—	0.13	0.18
17	—	1372	—	—	—	—	154	—	—	0.14	0.19
18	—	1581	—	—	—	—	137	—	—	0.16	0.21
19	—	1621	—	—	—	—	140	—	—	0.15	0.20
20	—	1505	—	—	—	—	141	—	—	0.13	0.18
21	—	1552	—	—	—	—	146	—	—	0.16	0.21
22	—	2361	—	—	—	—	146	—	—	0.13	0.18
23	—	1947	—	—	—	—	161	—	—	0.12	0.16
24	—	2256	—	—	—	—	171	—	—	0.15	0.20
25	—	1858	—	—	—	—	146	—	—	0.13	0.17
26	—	—	—	—	—	—	—	25	—	—	—
27	—	—	—	—	—	—	—	17	—	—	—
28	—	—	—	—	—	—	—	16	—	—	—

Table 62. Summary of test results from in-situ testing – SH 99

	Stabilized Subgrade						Natural Subgrade			FWD Deflection	
	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	E_{LWD}	CBR	D_0	$D_{0\text{-Cor.}}$
PT	%	MPa	MPa	MPa	MPa	mm	MPa	MPa	%	mm	mm
1	175	337	—	—	—	211	244	—	24	0.13	0.18
2	—	366	—	—	—	—	312	—	—	0.11	0.16
3	—	390	—	—	—	—	251	—	—	0.12	0.18
4	—	324	—	—	—	—	239	—	—	0.13	0.19
5	—	433	—	—	—	—	267	—	—	0.12	0.17
6	—	330	—	—	—	—	270	—	—	0.11	0.16
7	—	276	—	—	—	—	245	—	—	0.16	0.23
8	—	289	—	—	—	—	241	—	—	0.12	0.18
9	—	417	—	—	—	—	270	—	—	0.12	0.17
10	—	348	—	—	—	—	191	—	—	0.18	0.25
11	—	412	—	—	—	—	222	—	—	0.13	0.19
12	—	323	—	—	—	—	197	—	—	0.19	0.27
13	—	273	—	—	—	—	220	—	—	0.14	0.20
14	—	308	—	—	—	—	185	—	—	0.15	0.21
15	—	273	—	—	—	—	251	—	—	0.11	0.16
16	—	290	—	—	—	—	258	—	—	0.12	0.17
17	—	458	—	—	—	—	249	—	—	0.13	0.19
18	—	496	—	—	—	—	342	—	—	0.13	0.19
19	—	637	—	—	—	—	233	—	—	0.14	0.20
20	—	1000	—	—	—	—	268	—	—	0.11	0.16
21	—	268	—	—	—	—	234	—	—	0.17	0.24
22	—	328	—	—	—	—	261	—	—	0.14	0.20
23	—	320	—	—	—	—	252	—	—	0.14	0.20
24	—	389	—	—	—	—	254	—	—	0.14	0.20
25	—	419	—	—	—	—	240	—	—	0.15	0.21
26	—	273	—	—	—	—	195	—	—	0.16	0.23
27	—	533	—	—	—	—	232	—	—	0.17	0.24
28	—	454	—	—	—	—	208	—	—	0.16	0.23
29	—	245	—	—	—	—	163	—	—	0.18	0.26
30	—	224	—	—	—	—	200	—	—	0.15	0.22
31	—	297	—	—	—	—	205	—	—	0.16	0.23
32	—	459	—	—	—	—	232	—	—	0.16	0.22
33	—	296	—	—	—	—	214	—	—	0.17	0.24
34	—	554	—	—	—	—	234	—	—	0.16	0.23
35	—	324	—	—	—	—	249	—	—	0.15	0.22

	Stabilized Subgrade						Natural Subgrade			FWD Deflection	
36	—	317	—	—	—	—	264	—	—	0.15	0.21
37	—	390	—	—	—	—	238	—	—	0.14	0.21
38	—	268	—	—	—	—	243	—	—	0.15	0.22
39	—	413	—	—	—	—	245	—	—	0.15	0.21
40	—	312	—	—	—	—	219	—	—	0.18	0.25
41	77	260	—	—	—	176	229	—	36	0.17	0.24
42		271	—	—	—	—	232	—	—	0.16	0.23
43	156	314	—	—	—	246	198	—	—	0.18	0.26
44	79	425	—	—	—	256	277	—	52	0.13	0.19
45	30	263	107	63	149	213	233	—	23	0.15	0.21
46	—	—	—	—	—	—	—	16	29	—	—

Table 63. Summary of test results from in-situ testing – US 59

	Base	Stabilized Subgrade						Natural Subgrade			FWD Deflection	
	E_{LWD}	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	E_{LWD}	CBR	$D_{0\text{-}Cor.}$	D_0
PT	MPa	%	MPa	MPa	MPa	MPa	mm	MPa	MPa	%	mm	mm
1	—	—	994	—	—	—	—	339	—	—	0.21	0.20
2	—	—	646	—	—	—	—	339	—	—	0.22	0.20
3	—	—	1400	—	—	—	—	430	—	—	0.30	0.28
4	—	141	1054	—	—	—	96	373	—	30	0.27	0.25
5	—	—	700	—	—	—	—	425	—	—	0.20	0.18
6	—	—	978	—	—	—	—	265	—	—	0.21	0.19
7	—	—	586	—	—	—	—	206	—	—	0.23	0.21
8	—	—	640	—	—	—	—	244	—	—	0.24	0.22
9	—	—	655	—	—	—	—	563	—	—	0.23	0.22
10	—	—	562	—	—	—	—	489	—	—	0.19	0.18
11	—	—	776	—	—	—	—	420	—	—	0.19	0.18
12	—	105	1782	—	—	—	113	536	—	19	0.15	0.14
13	—	—	1411	—	—	—	—	525	—	—	0.15	0.14
14	—	—	731	—	—	—	—	523	—	—	0.13	0.12
15	—	—	658	—	—	—	—	382	—	—	0.18	0.16
16	—	166	572	—	—	—	180	409	—	19	0.15	0.14
17	—	—	642	—	—	—	—	509	—	—	0.15	0.14
18	—	—	649	—	—	—	—	398	—	—	0.17	0.16
19	—	—	1230	—	—	—	—	531	—	—	0.17	0.15
20	—	196	1365	—	—	—	251	447		32	0.15	0.14
21	—	—	575	—	—	—	—	543	—	—	0.15	0.14
22	—	—	627	—	—	—	—	392	—	—	0.17	0.16
23	—	—	689	—	—	—	—	351	—	—	0.19	0.18
24	126	106	933	105	177	261	124	210	20	14	0.23	0.21
25	—	—	879	—	—	—	—	280	—	—	0.27	0.25
26	—	—	567	—	—	—	—	244	—	—	0.23	0.22
27	—	—	489	—	—	—	—	244	—	—	0.20	0.19
28	—	119	613	—	—	—	136	311	—	21	0.21	0.19
29	—	—	644	—	—	—	—	344	—	—	0.20	0.19
30	—	—	692	—	—	—	—	343	—	—	0.22	0.21
31	—	—	664	—	—	—	—	216	—	—	0.29	0.27
32	—	—	—	—	—	—	—	—	33.7	27	—	—
33	—	—	—	—	—	—	—	—	17.1	—	—	—
34	—	—	—	—	—	—	—	—	25.1	—	—	—

Table 64. Summary of test results from in-situ testing – US 75 SB

	Stabilized Subgrade						**Natural Subgrade**		**FWD Deflection**	
	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi	E_{FWD}	CBR	D_0	$D_{0\text{-Cor.}}$
PT	%	MPa	MPa	MPa	MPa	mm	MPa	%	mm	mm
1	—	926	—	—	—	—	436	—	0.10	0.16
2	—	818	—	—	—	—	376	—	0.11	0.16
3	—	945	—	—	—	—	437	—	0.11	0.16
4	82	921	—	—	—	95	460	29	0.08	0.12
5	—	879	—	—	—	—	427	—	0.08	0.13
6	—	1260	—	—	—	—	420	—	0.09	0.14
7	—	1084	—	—	—	—	452	—	0.08	0.13
8	—	1072	—	—	—	—	387	—	0.09	0.14
9	—	871	—	—	—	—	467	—	0.09	0.13
10	—	1168	—	—	—	—	369	—	0.10	0.16
11	9	453	—	—	—	—	297	13	0.14	0.22
12	—	1047	—	—	—	—	319	—	0.12	0.18
13	—	1019	—	—	—	—	308	—	0.12	0.18
14	—	396	—	—	—	—	292	—	0.14	0.20
15	—	472	—	—	—	—	279	—	0.14	0.21
16	—	428	—	—	—	—	266	—	0.14	0.21
17	—	1604	—	—	—	—	298	—	0.12	0.19
18	14	945	31	7	15	120	350	6	0.11	0.17
19		949	—	—	—		313		0.14	0.21
20	12	573	—	—	—	140	270	6	0.16	0.25
21	—	487	—	—	—	—	275	—	0.15	0.22
22	—	511	—	—	—	—	288	—	0.15	0.23
23	—	588	—	—	—	—	299	—	0.15	0.23
24	—	462	—	—	—	—	317	—	0.12	0.19
25	—	476	—	—	—	—	218	—	0.14	0.22
26	—	488	—	—	—	—	218	—	0.16	0.24
27		531	—	—	—	—	229	—	0.16	0.24
28	18	572	—	—	—	—	226	6	0.17	0.26
29	—	508	—	—	—	—	268	—	0.15	0.22
30	—	510	—	—	—	—	271	—	0.13	0.20
31	—	545	—	—	—	—	311	—	0.14	0.22
32	—	482	—	—	—	—	337	—	0.11	0.17
33	—	534	—	—	—	—	351	—	0.12	0.18
34	54	1640	—	—	—	—	287	9	0.12	0.18
35		461	—	—	—	—	266		0.14	0.21

	Stabilized Subgrade						Natural Subgrade		FWD Deflection	
36	—	434	—	—	—	—	297	—	0.13	0.20
37	—	452	—	—	—	—	301	—	0.13	0.20
38	—	422	—	—	—	—	291	—	0.13	0.19
39	—	459	—	—	—	—	272	—	0.14	0.21
40	—	779	—	—	—	—	372	—	0.10	0.16
41	—	475	—	—	—	—	247	—	0.15	0.23
42	—	415	—	—	—	—	262	—	0.14	0.22
43	—	681	—	—	—	—	297	—	0.12	0.18
44	—	742	—	—	—	—	359	—	0.12	0.18
45	19	400	—	—	—	—	259	7	0.14	0.21
46	—	451	—	—	—	—	293	—	0.14	0.21
47	—	835	—	—	—	—	363	—	0.10	0.15
48	—	671	—	—	—	—	307	—	0.13	0.20
49	—	835	—	—	—	—	420	—	0.10	0.16
50	—	896	—	—	—	—	428	—	0.11	0.16

Table 65. Summary of test results from in-situ testing – US 75 NB

	Base	Stabilized Subgrade						Natural Subgrade		FWD Def.	FWD Modulus
	E_{LWD}	CBR	E_{V1}	E_{V2}	E_{LWD}	Thi.		E_{LWD}	CBR	D_0	E_{sg}
PT	MPa	%	MPa	MPa	MPa	mm		MPa	%	mm	MPa
1	—	—	—	—	—	—		—	—	0.13	156
2	—	—	—	—	—	—		—	—	0.20	162
3	—	13	—	—	—	132		—	7	0.14	154
4	—	—	—	—	—	—		—	—	0.20	161
5	—	—	—	—	—	—		—	—	0.12	180
6	—	—	—	—	—	—		—	—	0.16	191
7	—	—	—	—	—	—		—	—	0.11	187
8	—	—	—	—	—	—		—	—	0.14	225
9	—	—	—	—	—	—		—	—	0.12	172
10	—	—	—	—	—	—		—	—	0.17	191
11	—	17	—	—	—	115		—	9	0.11	192
12	—	—	—	—	—	—		—	—	0.15	208
13	—	—	—	—	—	—		—	—	0.13	156
14	—	—	—	—	—	—		—	—	0.17	177
15	—	—	—	—	—	—		—	—	0.13	163
16	—	—	—	—	—	—		—	—	0.17	167
17	—	—	—	—	—	—		—	—	0.12	158
18	—	—	—	—	—	—		—	—	0.18	175
19	—	—	—	—	—	—		—	—	0.12	165
20	—	—	—	—	—	—		—	—	0.16	196
21	—	—	—	—	—	—		—	—	0.13	147
22	—	—	—	—	—	—		—	—	0.17	177
23	—	—	—	—	—	—		—	—	0.13	153
24	—	—	—	—	—	—		—	—	0.19	175
25	81	—	81	119	91	—		—	—	0.12	176
26	—	—	—	—	—	—		—	—	0.17	189
27	—	—	—	—	—	—		—	—	0.13	158
28	—	—	—	—	—	—		—	—	0.16	181
29	—	—	—	—	—	—		—	—	0.12	164
30	—	—	—	—	—	—		—	—	0.18	180
31	—	26	—	—	—	125		—	9	0.14	150
32	—	—	—	—	—	—		—	—	0.18	170
33	—	—	—	—	—	—		—	—	0.13	157
34	—	—	—	—	—	—		—	—	0.17	172
35	—	—	—	—	—	—		—	—	0.11	143

	Base	Stabilized Subgrade					Natural Subgrade		FWD Def.	FWD Modulus
36	—	—	—	—	—	—	—	—	0.18	167
37	—	—	—	—	—	—	—	—	0.13	153
38	—	—	—	—	—	—	—	—	0.17	168
39	—	—	—	—	—	—	—	—	0.13	152
40	—	—	—	—	—	—	—	—	0.18	164
41	—	—	—	—	—	—	—	—	0.11	180
42	—	—	—	—	—	—	—	—	0.16	187
43	—	26	—	—	—	153	—	6	0.10	178
44	—	—	—	—	—	—	—	—	0.14	210
45	—	—	—	—	—	—	—	—	0.12	164
46	—	—	—	—	—	—	—	—	0.16	180
47	—	—	—	—	—	—	—	—	0.11	159
48	—	—	—	—	—	—	—	—	0.17	179
49	—	19	—	—	—	116	—	8	0.11	159
50	—	—	—	—	—	—	—	5	0.16	182

Table 66. Summary of test results from in-situ testing – K 7

	Stabilized Subgrade						**Natural Subgrade**			**FWD Deflection**	
	CBR	E_{FWD}	E_{LWD}	E_{V1}	E_{V2}	Thi.	E_{FWD}	E_{LWD}	CBR	D_0	$D_{0\text{-Cor.}}$
PT	%	MPa	MPa	MPa	MPa	mm	MPa	MPa	%	mm	mm
1	96	399	—	—	—	207	113	—	14	0.21	0.32
2	—	453	—	—	—	—	123	—	—	0.23	0.34
3	—	530	—	—	—	—	131	—	—	0.23	0.35
4	94	527	—	—	—	463	160	—	22	0.21	0.32
5	—	446	—	—	—	—	152	—	—	0.20	0.31
6	—	563	—	—	—	—	141	—	—	0.23	0.35
7	—	485	—	—	—	—	144	—	—	0.21	0.32
8	—	453	—	—	—	—	144	—	—	0.21	0.31
9	—	461	—	—	—	—	134	—	—	0.22	0.33
10	—	465	—	—	—	—	136	—	—	0.21	0.33
11	51	486	89	137	294	—	143	—	—	0.22	0.33
12	—	445	—	—	—	—	142	—	—	0.21	0.31
13	—	423	—	—	—	—	132	—	—	0.20	0.31
14	—	420	—	—	—	—	139	—	—	0.21	0.31
15	—	442	—	—	—	—	128	—	—	0.22	0.33
16	68	453	—	—	—	329	155	—	10	0.20	0.31
17	—	522	—	—	—	—	150	—	—	0.21	0.33
18	—	542	—	—	—	—	143	—	—	0.22	0.34
19	—	495	—	—	—	—	149	—	—	0.21	0.32
20	—	480	—	—	—	—	148	—	—	0.21	0.32
21	—	470	—	—	—	—	151	—	—	0.21	0.31
22	—	503	—	—	—	—	158	—	—	0.21	0.32
23	—	602	—	—	—	—	143	—	—	0.22	0.33
24	—	512	—	—	—	—	140	—	—	0.23	0.34
25	—	575	—	—	—	—	136	—	—	0.24	0.36
26	—	580	—	—	—	—	130	—	—	0.25	0.37
27	—	568	—	—	—	—	127	—	—	0.25	0.42
28	—	685	—	—	—	—	125	—	—	0.27	0.44
29	52	214	—	—	—	209	116	—	—	0.29	0.39
30	—	708	—	—	—	—	121	—	—	0.26	0.40
31	—	674	—	—	—	—	110	—	—	—	—
32	—	—	—	—	—	—	—	12	—	—	—
33	—	—	—	—	—	—	—	10	—	—	—

APPENDIX G: CONSTRUCTION RECORD

Table 67. Field nuclear density test at the US 183 site

SHRP-2

JOB ____
SHEET NO. ____ OF ____
CALCULATED BY ____ DATE ____
CHECKED BY ____ DATE ____
SCALE ____

WASHITA CO. US-183 @ TEST LOCATION

			DEN. TEST		DD	WD
	PROCTOR	OPT.%	% COMPAC	% M		
407+00	103.6	21.3	102.6	19.0%	106.3	126.4
414+00	103.3	21.1	101.4	17.2%	108.8	127.5

126.4 x .62 x 8 = 762.19

Table 68. Compaction test results at the SH 99 site

DH Form 393-92

COMPACTION TEST #

Project No. NHY-12N (005) County Sem. Div. 3

Date 2-15-2000 Tested By O.J. AASHTO T-99 Method A

COMPACTED DENSITY DETERMINATIONS

Water Added		64	64			
Gross Weight		3812.1	3872.2	3845.7		
Tare Weight		1925.3	1925.3	1925.3		
Net Weight		1886.8	1946.9	1920.4		
Wet Den. Lbs./Cu. Ft.		124.24	128.20	126.46		
Dry Den. Lbs./Cu. Ft.		107.87	109.84	106.19		109.11
MOISTURE DETERMINATIONS						M-W
Dish No.		5	200	4		200
Dish - Wet		162.63	158.23	160.55		158.23
Dish - Dry		145.09	139.46	139.77		139.23
Water		17.54	18.17	20.76		19.00
Dish - Dry		145.09	139.46	139.77		139.23
Dish		29.50	30.76	31.00		30.76
Dry Soil		115.59	108.70	108.77		108.47
% Moist.		15.17	16.71	19.09		17.5

Material ______

Passing #4 sieve

Sample Wt. 7#

Mold Vol. 5.33 Kg/m3

Mold Factor .06585

new mold.

Remarks: Soil + Flyash Final Mix

Standard Dry Density 109.1 PCF

Optimum Moisture 17.5 %

DH Form 393-92

COMPACTION TEST #

Project No. NHY-12N (005) County Sem. Div. 3

Date 1-18-2K Tested By OJ AASHTO T-99 Method A

COMPACTED DENSITY DETERMINATIONS

Water Added						
Gross Weight	3793.7	3814.2	3774.7			
Tare Weight	1815.8	1815.8	1815.8			
Net Weight	1977.9	1998.4	1958.9			
Wet Den. Lbs./Cu. Ft.	130.74	132.09	129.48			
Dry Den. Lbs./Cu. Ft.	114.70	113.75	109.40			
MOISTURE DETERMINATIONS						
Dish No.	20	4	10	1		
Dish - Wet	171.48	160.25	159.50			
Dish - Dry	154.21	142.30	139.65			
Water	17.27	17.95	19.85			
Dish - Dry	154.21	142.30	139.65			
Dish	30.66	31.00	30.25	29.36		
Dry Soil	123.55	111.30	109.40			
% Moist.	13.98	16.12	18.14			

Material Air dried

Passing #4 sieve

Sample Wt. 7#

Mold Vol. 5.33 Kg/m3

Mold Factor .0661 Kg/m3

Remarks: Flyash + Soil Final Mix STA-5108+00 - To 5127+00

Standard Dry Density 114.7 PCF

Optimum Moisture 13.9

Table 69. Field nuclear density test at the SH 99 site (1)

TROXLER LABORATORIES

NUCLEAR COMPACTION TEST DATA

PROJECT NHYRN(605)
JOB NUMBER
DATE
TAKEN BY A. Moore

TEST NUMBER	1	2	3	4	5	6	7	8	9	10
(date)	1-6-00		1-11-00	1-?5-00		1-17-00	1-19-00		2-11-00	
STATION	5092+00	5090+75	5096+75	Base LINE	5103+15	5108+75	5113+50	5119+33	5122+10	5126+00
OFFSET	14' Lt	Lt 24'	Lt 17'	℄	℄	2' Rt	5' Rt	4' Lt	16' LT ℄	6' LT ℄
ELEVATION	Sub F/Ash	Sub F/Sub	Sub F/Ash	Sub Fly/Ash	Sub F/Ash	Sub F/Ash	Sub F/Ash	Sub F/Ash	Sub/F Ash	Sub/F Ash
MODE & DEPTH	8"	8"	8"	8"	8"	8"	8"	8"	8"	8"
DENS. CNT.	1346	1388	1209	1240	1242	1298	1200	1170	1245	1545
WET DENS.	123.2	122.0	127.7	126.7	126.7	125.1	128.0	128.9	129.5	121.6
MSTRE. CNT.	220	218	197	198	185	182	142	153	178	173
MOISTURE	21.4	21.2	18.9	19.0	17.6	17.3	13.0	14.2	14.3	13.9
DRY DENS.	101.7	100.8	108.8	107.7	109.1	107.7	115.0	114.7	115.1	107.7
% MOISTURE	21.1	21.1	17.4	17.7	16.2	16.1	11.3	12.3	12.4	12.9
STD. DENS.	97.6	97.6	97.6	107.4	107.4	107.4	114.7	114.7	114.7	106.9
OPT. MSTRE.	24.6	24.6	24.6	19.3	19.3	19.3	13.9	13.9	13.9	11.5
% COMP.	104.2	103.3	101.3	100.3	100.5	100.3	100.2	100.0	100.4	100.7
MSTRE. CORR.	RETAKE	RETAKE								

TEST NUMBER	11	12	13	14	15	16	17	18	19	20
(date)	2-10-2000			2-16	3-6-00	3-10-00	3-14-00		4-7-00	4-8-00
STATION	EW119	5160	EW Ctyrd	5130+75	5134+10	5042+00	5147+50	5151+08	5156+50	5160+35
OFFSET	10' LT ℄	12 Rt ℄	.	℄	7' Lt	℄	5' Lt ℄	8' Lt ℄	5' Lt	℄
ELEVATION	Clay sub	clay Sub	Clay Sub	Sub F/Ash	Sub F/Ash	Sub Fly/Ash	Fly/Ash Sub	Fly/Ash	Fly Ash	FLY ASH
MODE & DEPTH	6"	6"	8"	8"	8"	8"	8"	8"	8"	8"
DENS. CNT.	1821	1887	1279		1444	2185	1288	1443	1453	1456
WET DENS.	131.5	130.1	128.4	127.6	123.6	123.6	128.2	123.7	129.5	129.9
MSTRE. CNT.	179	151	162		249	241	165	223	189	184
MOISTURE	14.5	11.9	12.9	16.6	20.9	20.4	13.4	18.7	20.6	15.1
DRY DENS.	117.0	118.2	115.4	111.0	102.7	103.2	114.8	105.0	108.9	114.8
% MOISTURE	12.4	10.1	11.2	14.9	20.3	19.7	11.7	17.8	18.9	13.2
STD. DENS.	116.9	115.5	115.5	109.1	101.4	101.4	114.7	104.2	107.4	114.7
OPT. MSTRE.	12.4	12.4	12.4	17.5	21.2	21.2	13.9	19.6	19.3	13.9
% COMP.	100.1	102.3	99.9	101.8	101.3	101.8	100.1	100.8	101.4	100.4
MSTRE. CORR										

DENSITY	MOISTURE

REMARKS:

Table 70. Field nuclear density test at the SH 99 site (2)

SUBGRADE

PROJECT: DSB-40A(424) 588+86 – 594+86 57.08' x 0.67'

9 LOADS (240.13 TONS)

DATE: 5-7-99

TESTED BY: AKERS

FLYASH/SOIL OPERATION

STANDARD COUNT

DENSITY COUNT: 2906

MOISTURE COUNT: 516

DENSITY COUNT								
TEST NO.	1	2	3					
DEPTH OF TEST	6"	6"	6"					
STATION	590+00	592+00	594+00					
LOCATION	S. BOUND LANES	S. BOUND LANES	S. BOUND LANES					
WET DENSITY	128.6	125.0	124.4					
DRY DENSITY	113.6	109.2	108.4					
% MOISTURE	13.1	14.5	14.7					
STANDARD DRY DENSITY	107.3	107.3	107.3					
OPTIMUN MOISTURE	15.9	15.9	15.9					
COMPACTION % PR	105.9	101.8	101.1					
COMPACTION REQUIRED	100	100	100					
REMARKS	COMPACTION PASSES	PASS	PASS					
	STA 588+00 TO STA 591+00	STA 591+00 STA 593+00	593+00 595+00					

Rec'd 5-[illegible] 9 Q.D.0

Table 71. Field nuclear density test at the SH 99 site (3)

NUCLEAR FIELD DENSITY WORK SHEET

SUBGRADE

S.B

594+86 – 599+05 57.08' WIDE x .67 DEEP

6 LOADS (167.21 TONS)

JECT: DSB-40A (424)

TE: 5-13-99

STED BY: RK DARNeal

STANDARD COUNT

DENSITY COUNT: 2922

MOISTURE COUNT: 578

DENSITY COUNT	1014		870					
TEST NO.	1		2					
DEPTH OF TEST	BACK SCATTER		BACK SCATTER					
STATION	596+00		598+00					
LOCATION	CENTER OF INSIDE LT. LANE		CENTER OF OUTSIDE LT. LANE					
WET DENSITY	121.5		133.2					
DRY DENSITY	108.1		118.0					
% MOISTURE	12.4		12.9					
STANDARD DRY DENSITY	107.3		107.3					
OPTIMUN MOISTURE	15.9		15.9					
COMPACTION % PR	100.7%		110.00%					
COMPACTION REQUIRED	100 %		100 %					
REMARKS	OK		OK					

Table 72. Field nuclear density test at the SH 99 site (4)

NUCLEAR FIELD DENSITY WORK SHEET

SUBGRADE

S.B.
599+05 – 605+10
(242.13 TONS) LOADS ?

JECT: DSB-90A (424)
TE: 5-14-99
STED BY: RK Dorman

STANDARD COUNT
DENSITY COUNT: 2903
MOISTURE COUNT: 523

DENSITY COUNT	844		871		909			
TEST NO.	1		2		3			
DEPTH OF TEST	Back Scatter		Back Scatter		Back Scatter			
STATION	LT Lane's 600+00		602+00		604+00			
LOCATION	4' OFF ℄ OF Inside LT Lane		2' 6 FF ℄ outside RT. Lane		2' LT OF ℄ OF RT Lane's Inside Lane			
WET DENSITY	135.2		132.5		129.5			
DRY DENSITY	120.7		115.4		111.6 ~~122.5~~			
% MOISTURE	12.0		14.8		16.0			
STANDARD DRY DENSITY	107.3		107.3		107.3			
OPTIMUN MOISTURE	15.9		15.9		15.9			
COMPACTION % PR	112.0 %		107.6		104.0 %			
COMPACTION REQUIRED	100 %		100 %		100%			
REMARKS	OK		OK		OK			

5-17-99 O.R.O.