DRAFT REPO
(Item 2151; ORA 125-65

DURABILITY OF CHEMICALLY STABILIZED AGGREGATE BASES

Submitted to:
Dawn Sullivan
Planning and Research Division Engineer
Oklahoma Department of Transportation
200 N.E. 21st Street
Oklahoma City, Ok, 73105

Prepared by:
Naji N. Khoury
Musharraf M. Zaman
Gerald A. Miller

School of Civil Engineering and Environmental Science
The University of Oklahoma
Norman, Oklahoma 73019

From:
The Office of Research Administration
The University of Oklahoma
Norman, Oklahoma 73019

August 27, 2003

<u>The Technical Report Standard Title Page will be added later</u>

Disclaimer

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views of the Oklahoma Department of Transportation. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The authors would like to express their deepest appreciation to the Oklahoma Department of Transportation and the Federal Highway Administration for providing the funding for this research. The authors would also like to express their deepest gratitude to the Panel Members for providing help, guidance, patience, and support. Without their help and active involvement, this work would not have been successful.

The authors would like to thank the School of Civil Engineering and Environmental Science for providing all the necessary equipment and materials to pursue this research. A special thank goes to Mr. Mike Schmitz for his valuable assistance in the laboratory. The authors would also like to thank the undergraduate student, Chau-Yih Cheong, whose assistance in the laboratory was so valuable and efficient.

Authors are thankful to the Brazil Creek Minerals, Inc., in Fort Smith, Arkansas, Blue Circle Cement, Inc., in Tulsa, Oklahoma, and Boral Materials Technology, Oologah, Oklahoma, for supplying the fly ash and the cement kiln dust for this project. Finally, the authors are indebted to all the people at the quarries for their help in sampling and transporting aggregate materials.

Table of Contents

List of Tables

LIST OF FIGURES

List of Equations

SUMMARY

A comprehensive laboratory study was undertaken to investigate the effect of durability, namely, freeze-thaw (F-T) and wet-dry (W-D) cycles on raw and stabilized aggregate base. Four commonly used aggregates in Oklahoma, namely, Meridian (M), Richard Spur (RS), Sawyer (S), and Hanson (H), were used in this study. Aggregates were stabilized with different stabilizing agents. Resilient modulus and unconfined compressive strength (UCS) were the only measurements used to evaluate the effect of these actions. Additionally, laboratory tests such as Los Angeles abrasion and moisture-density were conducted to characterize the aggregates. The study was divided into two phases.

Phase I consists of evaluating the effect of F-T cycles and W-D cycles on Class C Fly Ash stabilized Meridian aggregate. One F-T cycle consisted of placing a specimen in a rapid F-T cabinet, then freezing it at –25°C (13°F) for 24 hours and thawing at 21.6°C (71°F) for another 24 hours with a relative humidity ranging between 90% and 95%. One wet/dry cycle consisted of placing a sample[1] in an oven at 71°C (160°F) for 24 hours, then placing it in a water bath for 24 hours at room temperature. The effect of F-T/W-D on stabilized samples was examined on 3-day and 28-day cured samples stabilized with 10% CFA. Two sets of samples were prepared. The first set, called Same Specimen (SS) set, was subjected to selected sequences of freeze-thaw or wet-dry cycles. The second set, called Different Specimens (DS) set, was subjected to a given sequence of F-T or W-D action and tested for Mr, followed by UCS test. The primary goal of this effort was to optimize/reduce the total number of samples needed for the testing program. The number of F-T/W-D cycles for the first set of specimens was 0, 4, 12, 30, and 60, while for the second set they were 0, 4, 12, and 30. Based on the results, it was observed that the resilient modulus of CFA-stabilized samples increased as the number of F-T/W-D cycles increased, up to a certain number, beyond which it started to decrease. Also, it was seen that the same samples could be used to evaluate the effects of F-T/W-D cycles on

[1] Sample (s) and Specimen (s) are used interchangeably in this report

resilient modulus of CFA-stabilized specimens as long as the number of Mr tests is low. In addition, the deleterious effect of W-D cycles on Mr values was higher than the effect of F-T cycles. And the effect of these actions had more deleterious effects on 28-day cured samples than on 3-day cured samples. The UCS tests were also used to identify the effect of F-T/W-D cycles. Tests were conducted on two sets of samples. For the first set (called Mr samples), tests were conducted on samples after subjecting them to a desired number of F-T or W-D cycles, followed by Mr testing. For the second set (called virgin samples), tests were directly conducted on samples after being subjected to 0, 4, 12, and 30 F-T or W-D cycles. It was seen that the unconfined compressive strength and modulus of elasticity values increased as the number of F-T/W-D cycles increased. It was also observed that samples subjected to resilient modulus tests had higher UCS and modulus of elasticity values than samples tested for only UCS.

The effect of F-T and W-D cycles was observed on raw specimens. Specimens were subjected to 4, 12, and 30 F-T cycles. It was observed that Mr values decreased as the number of F-T cycles increased. The maximum reduction in resilient modulus values was approximately 20%. On the other hand, raw samples could not withstand even one cycle of wetting/drying and Mr testing. From the observations in Phase I, the same specimens scheme was used in Phase II, in which, specimens were compacted at OAC, and cured for only 28 days.

Phase II consists of evaluating the effect of F-T cycles and W-D cycles on Meridian aggregate stabilized with CKD, FBA, and PC.; Richard Spur and Sawyer aggregates stabilized with CKD, CFA, and FBA; and Hanson aggregate stabilized with CKD, and FBA. In this phase, one F-T cycle consisted of placing a 28-day cured sample in a rapid F-T cabinet, then freezing it at –25°C (13°F) for 24 hours and thawing at 21.6°C (71°F) for another 24 hours with a relative humidity approximately 98%. During this phase, the membranes around the specimens were removed, so that moisture migration to specimens occurs more readily. One wet/dry cycle consisted of placing a 28-day cured specimen in an oven at 71°C (160°F) for 24 hours, then placing it in a water bath for 24 hours at room temperature. It was observed that Mr values decreased as the number of F-T cycles increased. The percentage decrease varied with the stabilized agents and aggregate type. CKD-stabilized specimens subjected to F-T/W-D cycles had the lowest Mr values, followed by CFA, FBA, and then PC. In addition, the performance of stabilized aggregate base under F-T cycles is a function of aggregate mineralogy. For example, Meridian, a limestone aggregate, had lower Mr values than Sawyer, a sandstone aggregate.

A commercially available software, Kenlayer, was used to evaluate the structural response of pavement as the resilient modulus of base changes due to stabilization and F-T/W-D cycles. Tensile strain at the bottom of the asphalt concrete layer and the compressive strain at the top of the subgrade were used to calculate corresponding allowable load repetitions (i.e., equivalent single axle load (ESAL)) and to evaluate these effects. Results showed that ESAL increased due to stabilization. It was also observed that a negative effect of F-T and W-D cycles on Mr produces a negative effect on ESAL and vice versus. In other words, an increase in Mr due to F-T/W-D cycles produces an increase in ESAL, while a decrease in Mr due to these cycles decreases the number of ESAL. In addition, the layer coefficients were determined using the traditional equation recommend by AASHTO, 1986. The effect of stabilization, aggregate mineralogy, F-T and W-D cycles, were observed on ESAL and the layer coefficient. Regression equations in tabular and graphical form are presented for predicting ESAL and layer coefficient of stabilized aggregate base for practical applications in pavement design. Such applications illustrated with design examples.

The reference intensity ratio (RIR) method was employed to identify and quantify the mass percent of minerals and cementing compounds in the stabilized specimens. Results show that the cementing compounds such as ettringite, gismondine, straetlingite, and tobermorite, among others, responsible for modulus increase, were formed and their amount varied from one stabilized specimens to another. The Mr values correlate fairly well with the sum of the cementing compounds. Finally, the SEM micrographs show the same trend as the XRD where the intensity of crystals formation is lower in CKD specimens than CFA, followed by FBA specimens.

The cost for constructing a section (1.83 m by 30.48 m; 6 ft by 100 ft), in the area of Oklahoma City, having an ESAL value of approximately 2,000,000, was determined. The costs for the materials, hauling, and compaction were provided by the companies. Results showed that the cost for constructing the section with raw aggregate is more expensive than a section stabilized with CKD, CFA, FBA, or PC. This due to the fact the stabilization reduced the thickness of the base layer, and thus, the bulk materials. It was also found that constructing a section with FBA is cheaper than a section with CFA, followed by CKD, and then PC.

1.1 Background

The demand for pavement networks in the United States is greater than ever, and the conditions of existing roadways are worsening due to heavier vehicles and increased volume. According to a 1997 Federal Highway Administration report, approximately 49% of rural interstate and approximately 60% of urban interstate pavements are rated between fair and poor (FHWA, 1997). There are other studies as well that indicate that the pavement condition of our highways is deteriorating rapidly (Comeau, 2001; Zhu, 1998; NCHRP, 1997; Pandey, 1996). In recent years many efforts have been directed toward making pavement systems perform better, function more smoothly, and last longer. One significant attempt was made in 1986 with the release of the AASHTO Design Guide of Pavement Structure, which intended to improve flexible pavement design methodology (AASHTO, 1986). Also, in recent years the pavement industry has focused on and has increasingly moved toward the development of mechanistic-based approaches of pavement design (Chen, 1994). Many Departments of Transportation have adopted the use of resilient modulus of associated layers in the design of pavement structures, rather than subgrade support values (Zhu, 1998). Resilient modulus is an important parameter in predicting the recoverable stresses, strains, and deflections in a flexible pavement (NCHRP, 1997). This can be determined using a laboratory cyclic triaxial test that simulates a repetitive moving traffic load over a pavement.

Aggregate base represents an important element in a flexible pavement structure (NCHRP, 1992; Uzan, 1999). It provides support for the asphalt concrete (AC) layer and protects the subgrade from overstressing. It is also believed that the quality of aggregate base can contribute to deterioration and premature failure of roadway pavements. Highway engineers have been faced with the problem of diminishing natural aggregate and good quality resources in Oklahoma. In some areas, the natural aggregate and good quality aggregate base are either too expensive or inaccessible. While in the other places aggregate base have to be transported from long distances, and thus, the total cost of the project increases. For these reasons, several studies have focused on the use of low quality, locally available aggregates, via chemical stabilization. As a result, it was found that chemical[2] stabilization can be used in pavement construction, helping with the disposal of industrial wastes, and reducing pavement distresses (Pandey, 1996; Yi, 1995; Zaman et al., 1998).

The response of a pavement system is influenced by many factors including, environmental factors, such as freeze-thaw (F-T) and wet-dry (W-D) conditions. In fact, variations in freeze-thaw and wet-dry conditions can have detrimental effects on the service life of a pavement system, and should be considered in its design. The AASHTO Design Guide includes an approximate method of addressing the effect of these factors on the resilient modulus of subgrade. However, the effects of seasonal factors (i.e., F-T and W-D cycles) on the aggregate base layer have received very little attention. As such, data on the variation of resilient modulus of stabilized aggregate base is extremely limited. Knowledge about the variation in resilient modulus of raw and stabilized aggregate base due to F-T and W-D cycles is expected to be helpful in the development of a rational design procedure for better pavement in Oklahoma.

1.2 Need for Durability of Chemically Stabilized Aggregate

It is stated in NCHRP (1992) that for "High Strength Stabilized Base (HSSB) material durability is a very important property and should be carefully considered in the HSSB mixture design process (In fact durability requirements may control the mixture design proportions)."

Zhu (1998) noted that

> "From the cited references, it becomes evident that there exists a need to address research on the resilient modulus versus the durability for stabilized aggregates. Effects of the number of both freezing/thawing and wetting/drying cycles on the resilient behavior of an aggregate remain an important area of research." (p. 19)

Little et al. (2001) reported

> "Given that many state DOTs now use compressive strength testing as the sole criterion for determining cement content in soil-cement, additional research is

---

[2] Chemical (ly) and Cementitious are used interchangeably in this report

needed to ensure that durability is also achieved at the specified strength for a variety of soil types. New durability tests may need to be developed for this purpose. A rapid and reliable test for assessing the impact of wet/dry and freeze/thaw cycles on durability remains a key need as well." (p. 7)

It is clear that the durability of chemically stabilized aggregate base remains a concern for many highway engineers and transportation agencies, and should be considered in pavement design. The experimental program undertaken in the present study is an attempt to address this concern.

1.3 Objectives

The primary objective of this study is to evaluate the effect of durability of chemically stabilized aggregate bases in Oklahoma. For this reason, four different types of aggregate, namely, Meridian (Limestone), Richard Spur (Limestone), Sawyer (Sandstone), and Hanson (Rhyolite) were stabilized with Cement Kiln Dust (CKD), Class C Fly Ash (CFA), Fluidized Bed Ash (FBA), and Portland Cement (PC). Stabilized aggregates were subjected to a different number of F-T and W-D cycles. The more specific tasks include the following:

(1) Identify a suitable laboratory procedure to evaluate the durability of chemically stabilized aggregates.

(2) Evaluate the deleterious effects of F-T and W-D cycles on the properties of the selected chemically stabilized aggregates: resilient modulus, unconfined compressive strength, and the layer coefficient.

(3) Quantify, for selected cases, the relative performance of different aggregate types (limestone, sandstone, and granite) under the F-T and W-D cycles.

(4) Determine the layer coefficient of the stabilized aggregate bases including the effect of F-T and W-D actions.

(5) Develop regression models for resilient modulus and layer of coefficients for potential field application.

(6) Use a commercially available computer program, Kenlayer, to evaluate the effect of CFA-stabilization on the flexible pavement design, using both fatigue and rutting

criteria. Also, evaluate the variation of base modulus (Mr) due to F-T/W-D cycles on the Equivalent Single Axle Load (ESAL).

2.1 General

This chapter is devoted to presenting the sources of materials that were used in this study. The coarse aggregates were collected during summer 1999 and the stabilizing agents were shipped to our laboratory from different agencies. The moisture-density tests were conducted on raw and stabilized aggregates to determine the optimum moisture content and maximum dry density. These results are presented in this chapter.

2.2 Aggregate Base

As mentioned previously, four different aggregate bases were used in this study: 1) Meridian (M); 2) Richard Spur (RS); 3) Sawyer (S); and 4) Hanson (H). M and RS aggregate are limestone aggregate with high percentage of calcium carbonate, and different mineral and fundamental properties. Conversely, S and H aggregates are considered as sandstone and rhyolite aggregates, respectively, with high silica content. Bulk aggregates were collected from different quarries and locations in Oklahoma. More than 100 bags, each having a weight of approximately 20kgs (44 lbs), were transported to the Broce laboratory and stored for testing. Figures 2-1 and 2-2 photographically depict the field sampling and storage of these materials, respectively. The mineralogy of each aggregate is given in Table 2-1.

2.3 Los Angeles Abrasion

The Los Angeles (L.A.) abrasion test is used to measure the degradation of mineral aggregates from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel balls, as reported in the ASTM C 131-96 method. The L.A. abrasion test was performed on raw aggregates in accordance with the ASTM C 131-96 method. A total of three tests were performed on each aggregate type and the average values are summarized in Table 2-1.

2.4 Moisture Density Test

Moisture-density tests were conducted according to the ASTM 1557-91 method. This test is used to determine the relationship between the moisture content and the dry density of a soil or aggregate mixture. A mechanical hammer was used for compaction. It was calibrated according to the ASTM D 2168-90 method, such that the ratio of maximum dry density (MDD) obtained using a manual compactor to MDD obtained using a mechanical compactor, was equal to or greater than 98%. Tests were conducted on raw aggregate and aggregate mixed with different percentages of stabilizing agents. A summary of the results is given in Table 2-2.

2.5 Stabilizing Agents

Cement Kiln dust (CKD), Class C Fly Ash (CFA), Fluidized Bed Ash (FBA), and Portland Cement (PC) were the main stabilizing agents used in this study. The difference among the additive properties brings different stabilization effects with different aggregate types, including the effect of F-T and W-D cycles.

2.5.1 Cement Kiln Dust

The cement kiln dust used was provided by Blue Circle Cement, Inc. (Lafarge is the current name of the company). Sealed buckets were shipped to our laboratory from Tulsa, Oklahoma. The cement kiln dust is collected from the exhaust gases of the cement kilns using bag houses. The physical and chemical properties are listed in Table 2-3.

2.5.2 Class C Fly Ash

Class C fly ash from Oologah was used in this study. CFA was brought into well-sealed plastic buckets. It was produced in a coal-fired electric utility plant. It has an average specific gravity of 2.69 and a loss on ignition (LOI) value of approximately 0.23%. The chemical and physical properties of CFA used in the present study were provided by Boral Materials Technologies and are well illustrated in Table 2-3.

2.5.3 Fluidized Bed Ash

Fluidized Bed Ash (FBA) was supplied by the Brazil Creek Minerals, Inc., Fort Smith, Arkansas. Sealed buckets were shipped to our laboratory. FBA is produced from the fluidized bed combustion process, in which low quality coal and coal washery wastes are burned in a fluidized bed combustor (Pandey, 1996). Properties of FBA are presented in Table 2-3.

2.5.4 Portland Cement

In this study, Type I Portland Cement was used. Portland cement is hydraulic cement produced by pulverizing clinker, consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfates as an integrated condition. No chemical tests were conducted to determine the PC chemical compounds; however, Table 2-3 illustrates the maximum values of different compounds, as recommended by ASTM C 150.

Table 2-1 Properties of the Aggregates Used in This Study

Compounds	Aggregates Properties			
	Percentage per weight, (%)			
	Meridian*	Richard Spur**	Sawyer***	Hanson****
SiO_2	0.25-6	9.53	92-95	60-67
Al_2O_3	---	0.49	---	10-13
Fe_2O_3	---	---	---	4.5-10
$CaCO_3$	91-98	86.9	---	---
CaO	---	---	---	1.4-2.8
MgO	0.7-1.2	---	---	0.3-0.5
Loss on ignition (LOI)	---	---	---	2-3
Specific gravity	2.67	2.67	2.87	2.65-2.68
Absorption	4-5	3.7	---	0.4-1.0
L.A. Abrasion value	34	26	22	18
* Marshal County				
** Comanche County				
*** Choctaw County				
**** Murray County				

Table 2-2 Moisture Density Test Results

Agrgegate Type	Maximum Dry Density, (pcf)	Optimum Moisture Content, w(%)
Meridian raw	140	6.50
Meridian with 15% CKD	131	8.80
Meridian with 10% CFA	138	7.00
Meridian with 10% FBA	134	8.80
Meridian with 3% PC	140	7.40
Richard Spur raw	151	3.34
Richard Spur with 15% CKD	142	5.53
Richard Spur with 10% CFA	147	4.00
Richard Spur with 10% FBA	144	6.00
Sawyer raw	144	4.00
Sawyer with 15% CKD	139	6.25
Sawyer with 10% CFA	140	5.00
Sawyer with 10% FBA	138	6.80
Hanson raw	144	5.50
Hanson with 15% CKD	137	8.65
Hanson with 10% FBA	138	7.30

Table 2-3 Properties of Stabilizing Agents Used in this Study

Stabilizing Agents Properties				
Compounds	Percentage per weight, (%)			
	CKD	CFA	FBA	PC
$SiO_2 + Al_2O_3 + Fe_2O_3$	19.23	62.1	35.3	---
Calcium oxide (CaO)	44.1	26.53	41.25	---
Magnesium oxide (MgO)	1.46	5.44	2.66	---
Sulphur oxide (SO_3)	2.49	2	19.31	3-3.5
Calcium carbonate ($CaCO_3$)	64.22	---	41	---
Free lime (CaO)	2-3	---	18.2	---
Loss on ignition (LOI)	29.38	0.23	5.34	<3
Percent fineness		11.5	55	---
Specific gravity	2.74	2.69	2.87	---

Figure 2-1 Aggregate Stockpile and Field Sampling

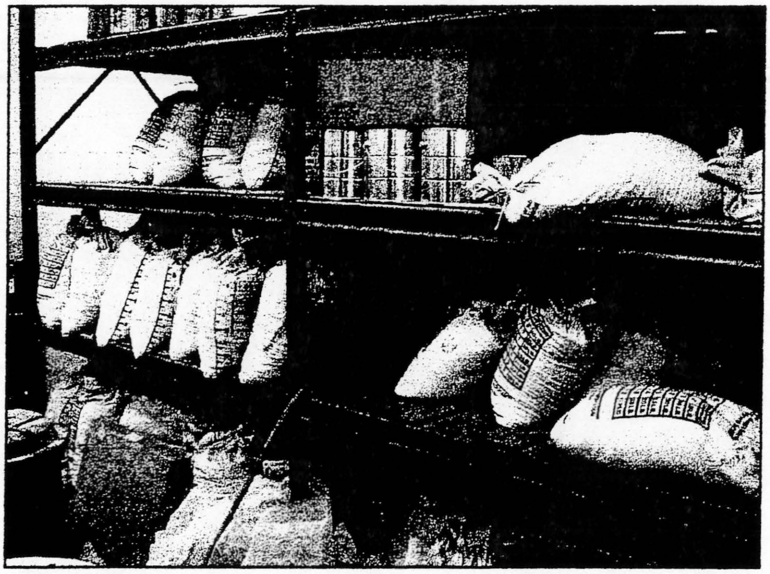


Figure 2-2 Storage of Meridian Aggregate in the Broce Laboratory

3.1 General

This chapter describes the experimental methodology that was followed to evaluate the effects of Freeze-Thaw and Wet-Dry cycles on the stabilized aggregate bases. Emphasis in this study is placed on resilient modulus (Mr) and shear strength presented by Unconfined Compressive Strength (UCS). Also, a description of sample preparation and compaction methods is included.

3.2 Testing Procedure for Resilient Modulus Laboratory

The resilient modulus tests were performed in accordance with the AASHTO T 292-91 method. The testing sequences were slightly modified, as given in Table 3-1, so the minimum deviator stress was be 69 kPa (10 psi). This modification is consistent with the NCHRP (1997) which recommends the minimum deviator stress be 69 kPa (10psi) when performed on base materials stabilized with lime-fly ash. The test involves applying between 200-500 cycles of a haversine-shaped load pulse with an amplitude of 130.5 kPa (15 psi), duration of 0.1 seconds and relaxation period of 0.9 seconds, as shown in Figure 3-1. A haversine load pulse, having the form of ([1-cos (θ)]/ 2), is shown in Figure 3-2 and is recognized as the best pulse shape to simulate the induced load shape in pavement layers by a moving vehicle (NCHRP, 1997). The above stress sequence is considered as sample conditioning that aids in eliminating the effect of interval between compaction and loading, as well as the effect of initial loading versus reloading (AASHTO, 1999). Subsequently, the sample was loaded following the sequences shown in Table 3-1. For each sequence, a total of 50 repetitions of the corresponding cyclic axial load using the same haversine load pulse were applied. The last five repetitions were recorded and used to determine the average resilient modulus values.

3.3 Sample Preparation

Two types of samples were prepared: unstabilized and stabilized. Unstabilized samples were molded only with raw aggregate, while stabilized specimens were prepared with aggregates mixed with additives. In both cases, samples were compacted using a modified vibratory compaction method, described in Khoury (2001), to reach the desired optimum moisture content (OMC) and the maximum dry density (MDD).

3.3.1 Stabilized Aggregate Mixture

Median gradation for type A aggregate base, recommended by the Oklahoma Department of Transportation's standard specification for Highway construction (ODOT, 1996), was used to prepare each sample and is depicted in Figure 3-3. Coarse aggregates, coarser than No. 4 sieve, were separated from fines, then washed and dried in an oven at 110°C (230°F) for 24 hours. Finer particles were only dried in the oven to make sure that the mixture was totally dry. After the drying process, the amount of additive was determined from the dry weight of the raw aggregate. Mixing the aggregate and additives was done in accordance with the following method to avoid any quick chemical/cementitious reactions. The method consisted of the following steps. In the first step, raw aggregates were mixed to uniformity. In the second step, 1/3 of the total amount of water was added and mixed with the aggregate. The third step consisted of adding and mixing half of the CFA to achieve a uniform mixture. In the fourth step, 1/3 of water was added and mixed. In the fifth step, the remaining CFA amount was added and mixed until a uniform mix was obtained. In the last step, the remaining water was added and mixed properly to obtain a uniform mixture. Figure 3-4 shows the photographic views of the mixing process. The mixture was then compacted according to the method illustrated in Khoury (2001). Figure 3-5 shows a photographic view of the mold assembled on a vibratory table. After compaction specimens were placed in a humidity room with controlled temperature and humidity, as shown in Figure 3-6.

3.4 Resilient Modulus Testing Apparatus

The resilient modulus test was performed using the MTS system in the Broce Laboratory. The loading system in MTS involves a servo-hydraulic testing machine capable of applying cyclic haversine-shaped load having a duration of 0.1 seconds and a rest period of 0.9 seconds. A Plexiglas chamber, having an internal diameter of 225 mm (9 in), was used. A load cell having 22.24 KN (5000 lbf) capacity was used and mounted inside the chamber. The load cell has an output of 2-mV/V and a resistance of 350 ohms. Both NCHRP (1997) and AASHTO (1999) recommended that a 152.4 mm (6 in) sample should be tested with a load cell having a maximum capacity of 22.24 KN (5000 lbf). The confining or cell pressure was provided by compressed air. The cell pressure was regulated and measured using a pressure gauge having an accuracy of 0.69 kPa (0.1psi) divisions.

For collecting data, such as load and displacement, a PCI 6052E data acquisition system, manufactured by National Instrument was used. This system consists of 16 analog input channels that can be used as eight differential input channels, with 16-bit resolution, and a sampling rate of 333kS/s. Also, it has two 16-bit analog outputs, eight digital I/O lines, and two 24-bit counters. These two channels can be used to send signal from the computer. In the current study, only three differential input channels were used: two for collecting the LVDT signals, and one to record the load applied to the sample. Also, one output channel was used to send the haversine-load pulse.

Internal linear variable differential transformers (LVDTs) were used to measure the vertical displacement of the samples. They were attached to two aluminum clamps that were mounted on the sample at a distance of 76.2 mm (3 in) from both ends of the sample. The LVDTs had a maximum stroke length of 5.08 mm (0.2 in). A power supply was used for exciting, and amplifying the LVDT signals. Figure 3-7 shows a photographic view of the LVDTs mounted on a sample. NCHRP (1997) rated the accuracy of determining the Mr values from internal LVDTs mounted on sample with clamps as good, overall. In addition, it was reported by NCHRP (1997) that internal LVDTs mounted directly on the specimen help reduce the extraneous deformations occurring outside of the specimen.

To generate the desired haversine-shaped load and to read the load and displacement signals, a software was written using Labview, G language, as shown in Figure 3-8. Data were collected and stored in an Excel file. A macro program in Excel was written to process these data and evaluate the resilient modulus. This software also generates graphical plots. The rate of data collection during the application of one cycle, i.e 0.1 seconds loading and 0.9 seconds rest was 230 points per second. Previous studies have shown that the use of 205 measurements over a one second interval gives more accurate results than for either 102 or 666 readings/sec. (NCHRP, 1997).

3.5 Noise Problems and Accuracy in Resilient Modulus Calculations

Noise is an important factor in resilient modulus testing. According to NCHRP (1997), there are two factors that help increase the noise-level in a resilient modulus test: (1) Sampling rate; and 2) Cross coupling between channels. One-way to remove or significantly reduce the noise-level associated with resilient modulus testing is through filtering, but it is discouraged to use this method. If not avoided, it is recommended that the frequency of filter be greater than 10 to 20 Hz (NCHRP, 1997; AASHTO, 1999). In addition, Zhu (1998) noted that the accuracy of resilient modulus results depends on the resolution of the data acquisition system, and LVDTs. In the current study, using ± 2.54 mm (± 0.1 in) LVDTs and 16-bit data acquisition, the resolution of the measured vertical displacement was $0.2/2^{16} = 3 * 10^{-6}$ in. The expected displacement for a stabilized specimen is generally between $25.4*10^{-4}$ mm (10^{-4} in) to $25.4*10^{-3}$ mm (10^{-3} in). So, the deviation of displacement or maximum relative error was in the range of $3 * 10^{-6} / 1*10^{-4}$ and $3 * 10^{-6} / 1*10^{-3}$ (3%-0.3%). Based on this calculation, no filter was needed to filter data because the possible error associated with the noise problem was considered negligible. Also, on more than three occasions, voltage values were recorded from LVDTs; the strain responses were calculated, and the standard deviation was calculated to verify if the noise levels were within the expected range. A summary of these data illustrated in Table 3-2 shows that noise signals were not interfering with the actual data.

3.6 Freeze-Thaw and Wet-Dry Cycles

Based on literature, there is no standard laboratory test procedure available to examine the effect of durability on the resilient modulus of CFA-stabilized aggregate. Consequently, an ad-hoc laboratory test method was used in this study, in which the F-T and W-D cycles were defined as follows:

One F-T cycle consisted of freezing the sample at a temperature of -25°C (-13°F) for 24 hours and thawing it at 21.6°C (71°F) for 24 hours with a relative humidity ranging between 90% and 95%. A rapid F-T cabinet, shown in Figure 3-9, was used for controlled freezing-thawing of samples. The temperature was lowered from 21.6°C (71°F) to -25°C (-13°F) in approximately one hour, and then held constant for 23 hours. For the thawing phase, the temperature was raised from -25°C (-13°F) to 21.6°C (71°F) in one hour and held constant for 23 hours. The variations of temperature in each cycle are shown schematically in Figure 3-10.

One W-D cycle consisted of placing the sample in an oven having a temperature of 71°C (160 °F) for 24 hours, and then submerging the sample in potable water for 24 hours at room temperature, as shown in Figures 3-11 and 3-12.

F-T and W-D cycles were applied on stabilized and on unstabilized raw aggregate specimens. The number of F-T or W-D cycles considered in this study was 4, 12, 30 and 60 (Phase I), while the number of cycles was 8, 16, and 30 in Phase II. At the end of each specified cycle, samples were tested for Mr, UCS, or both.

3.7 Unconfined Compressive Strength

The unconfined compressive strength (UCS) test was also performed to evaluate the effect of F-T and W-D cycles on CFA-stabilized aggregate base (Phase I). The significance of UCS of stabilized-soil specimens is to determine the suitability of mixture in pavement base and subbase applications (ASTM, 1998). The ASTM D 5102-96 test method was used to determine the unconfined compressive strength of CFA-stabilized aggregate base. The UCS tests were conducted, on a number of samples already tested for Mr; since the Mr test is a non-destructive test, this scheme is feasible. Also, a number of samples were tested for UCS on specimens not subjected to Mr testing. Samples were loaded at a constant strain rate equal to 1% per minute. Typical failure of a sample stabilized with lime is shown in Figure 3-13; the actual failure of a CFA-stabilized aggregate base specimen observed in the present study is shown in Figure 3-14. In addition, the strain values were recorded during testing so that the stress-strain data could be plotted and used to determine the modulus of elasticity of each sample.

Table 3-1 Testing Sequences Used in Resilient Modulus Testing

Sequence #	Confining Pressure kPa (psi)	Cyclic Deviator Stress kPa (psi)	Contact Stress kPa (psi)	Number of Cycles
0	138 (20)	104 (15)	27.6 (4)	200-500
1	138 (20)	69 (10)	27.6 (4)	50
2	138 (20)	138 (20)	27.6 (4)	50
3	138 (20)	207 (30)	27.6 (4)	50
4	138 (20)	276 (40)	27.6 (4)	50
5	104 (15)	69 (10)	27.6 (4)	50
6	104 (15)	138 (20)	27.6 (4)	50
7	104 (15)	207 (30)	27.6 (4)	50
8	104 (15)	276 (40)	27.6 (4)	50
9	69 (10)	69 (10)	27.6 (4)	50
10	69 (10)	138 (20)	27.6 (4)	50
11	69 (10)	207 (30)	27.6 (4)	50
12	69 (10)	276 (40)	27.6 (4)	50
13	34.5 (5)	69 (10)	27.6 (4)	50
14	34.5 (5)	138 (20)	27.6 (4)	50
15	34.5 (5)	207 (30)	27.6 (4)	50
16	34.5 (5)	276 (40)	27.6 (4)	50
17	0 (0)	69 (10)	27.6 (4)	50
18	0 (0)	138 (20)	27.6 (4)	50
19	0 (0)	207 (30)	27.6 (4)	50
20	0 (0)	276 (40)	27.6 (4)	50
Sequence # 0 is the specimen conditioning				

Table 3-2 Standard Deviation and Error of Strain During Mr Testing

Trial #	Standard Deviation, Strain (in/in)		
1	Sd = 10 psi	Sd = 20 psi	Sd = 40 psi
	3.17627E-06	6.14978E-06	5.10479E-06
	% Error		
	3.05	2.36	1.26
2	Sd = 10 psi	Sd = 20 psi	Sd = 40 psi
	2.42205E-06	3.32396E-06	4.37863E-06
	% Error		
	2.51	1.52	0.78
3	Sd = 10 psi	Sd = 20 psi	Sd = 40 psi
	3.63153E-06	4.04013E-06	4.84289E-06
	% Error		
	2.91	1.37	0.79

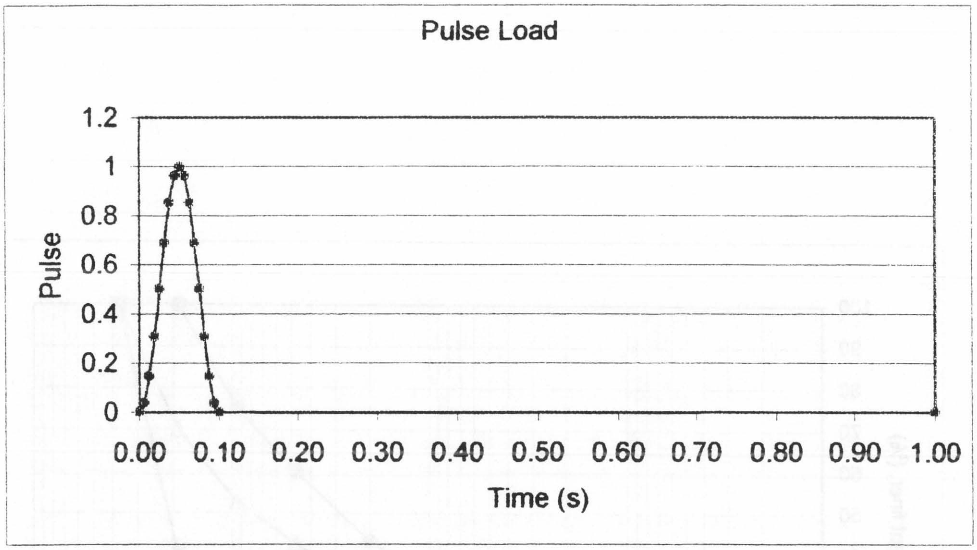


Figure 3-1 Cyclic Load Used in Resilient Modulus Testing

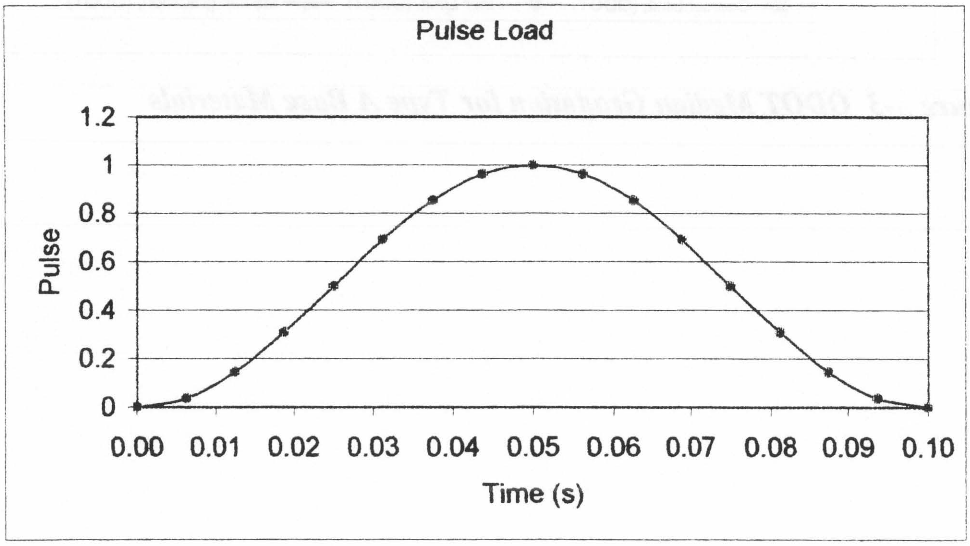


Figure 3-2 Haversine Pulse Load

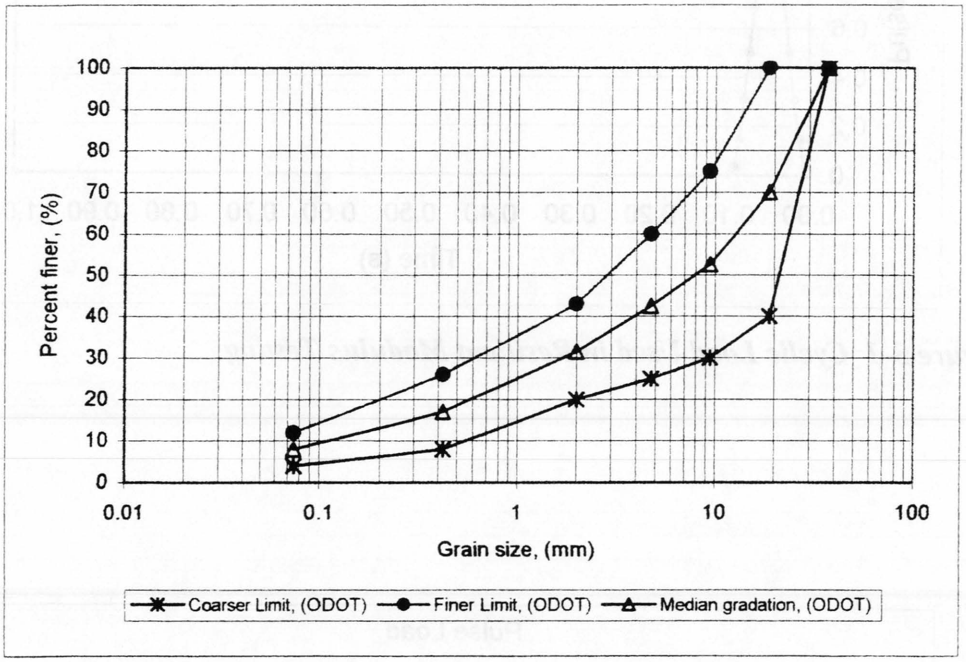
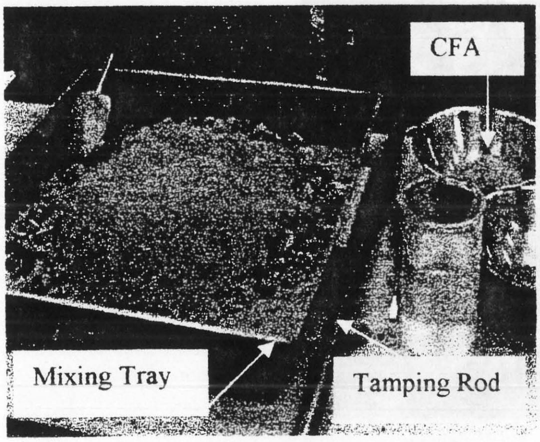
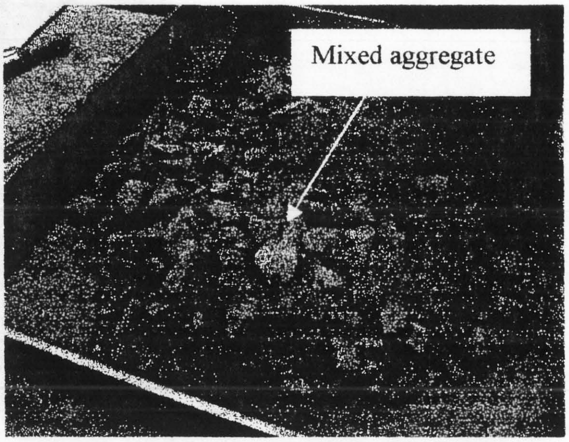


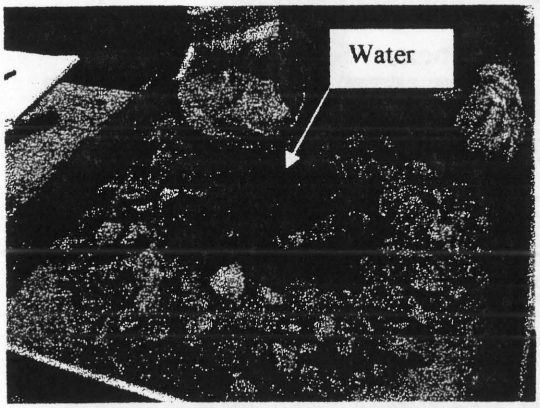
Figure 3-3 ODOT Median Gradation for Type A Base Materials



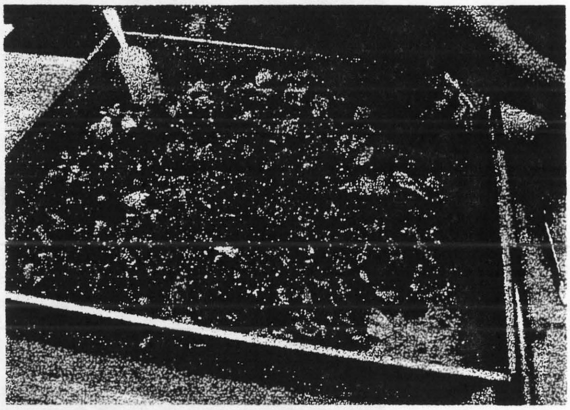
(a) *Photograph of Raw Aggregate, CFA, and Water Prior to Mixing*



(b) *Raw Aggregate Mixed to Uniformity*



(c) Water Added to the Mixture



(d) Aggregate, CFA and Water Mixture

Figure 3-4 Mixing Process

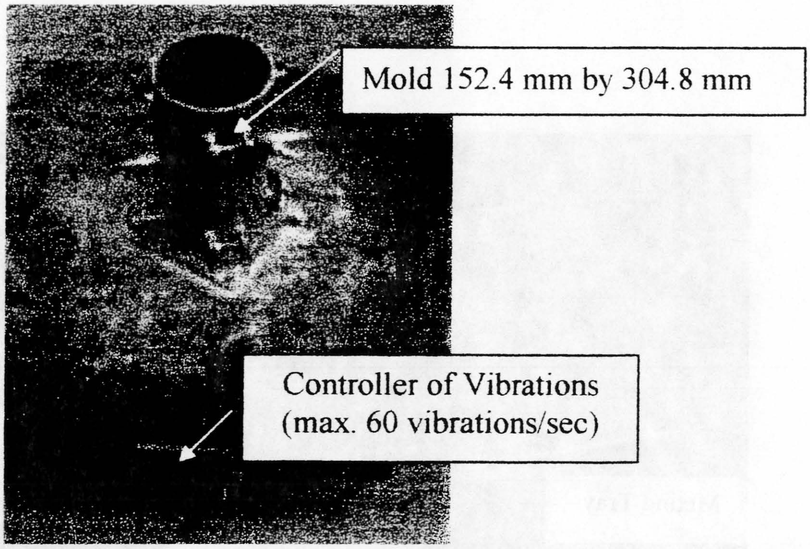


Figure 3-5 Mold Assembled on the Vibratory Table

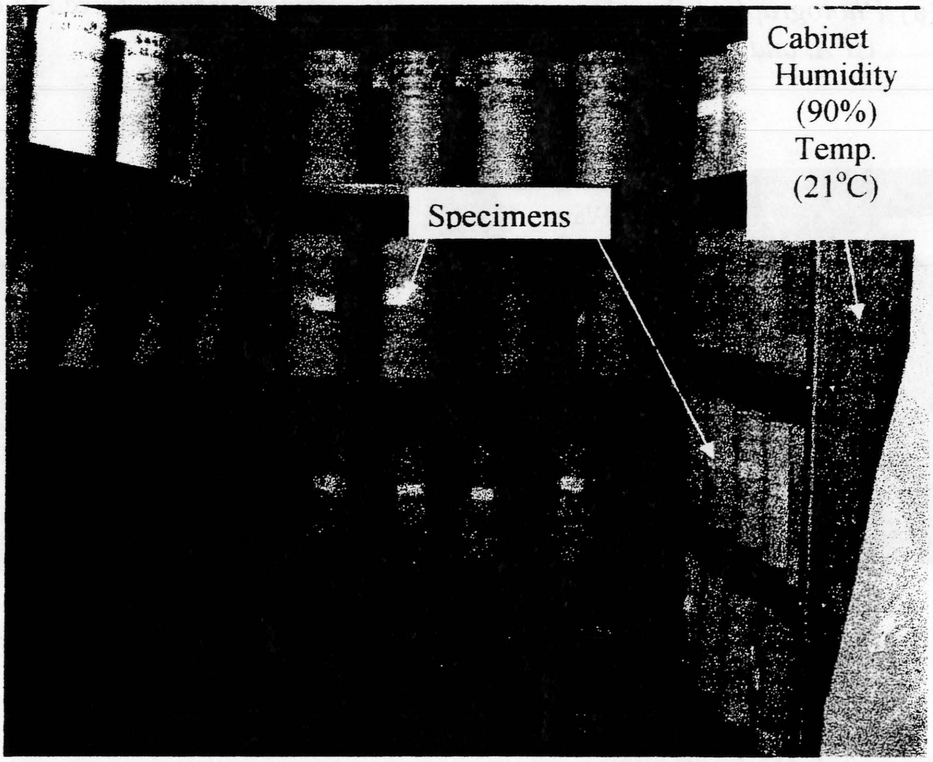


Figure 3-6 Samples Being Moist Cured in the Humidity Room

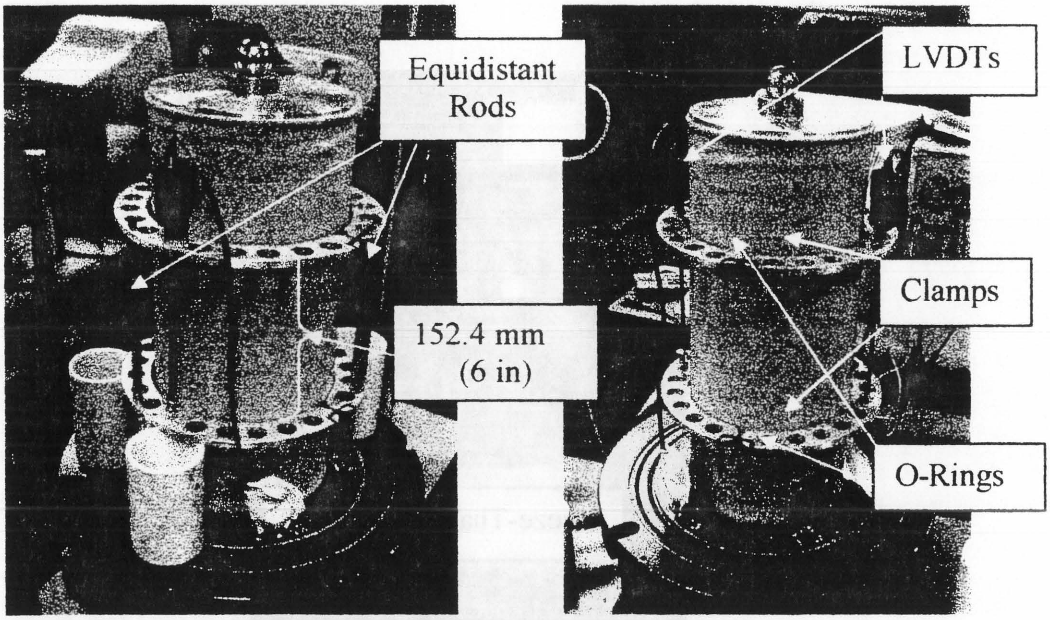


Figure 3-7 Photographic View of LVDT's Mounted on Samples

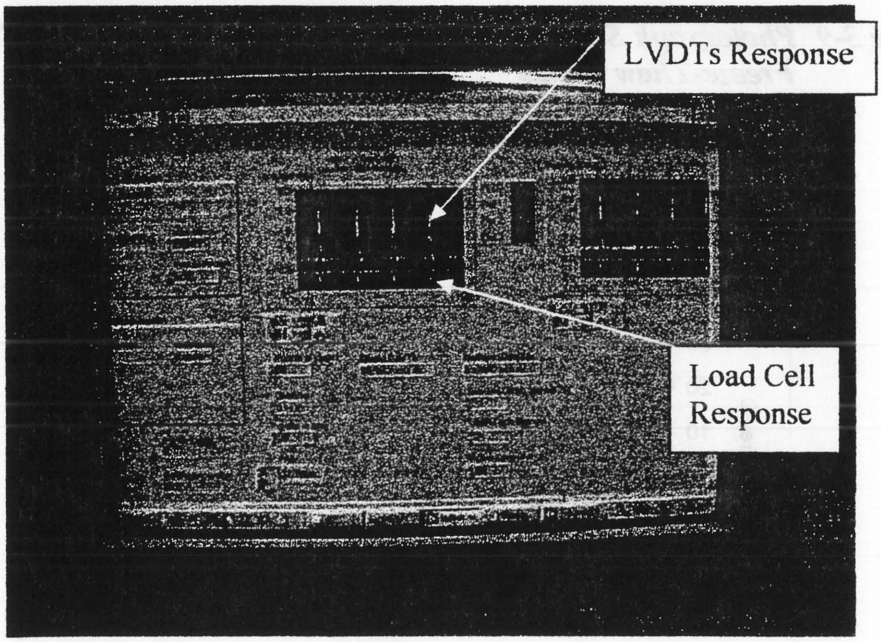


Figure 3-8 LabView Software Interface to Read and Send Signals from the Computer

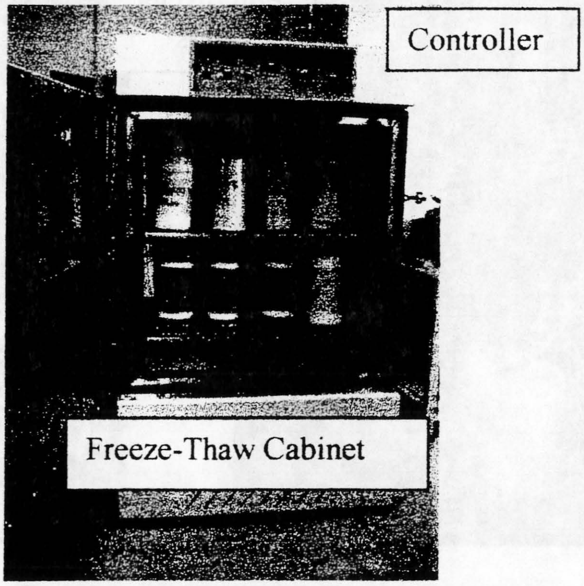


Figure 3-9 Photograph Showing Samples in a Freeze-Thaw Cabinet Subjected to Freeze-Thaw Cycles

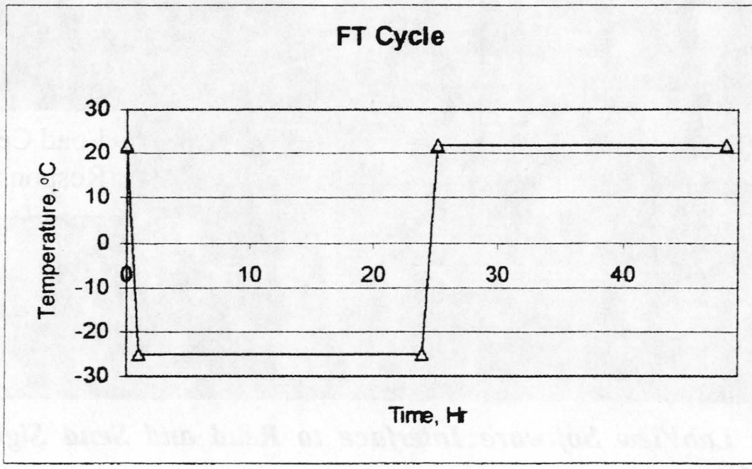


Figure 3-10 Definition of One Freeze-Thaw Cycle

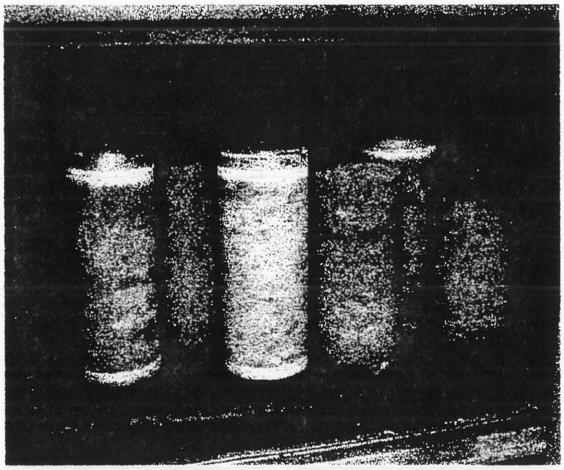


Figure 3-11 Photograph Showing Drying of Test Samples in an Oven at 71°C (160°F)

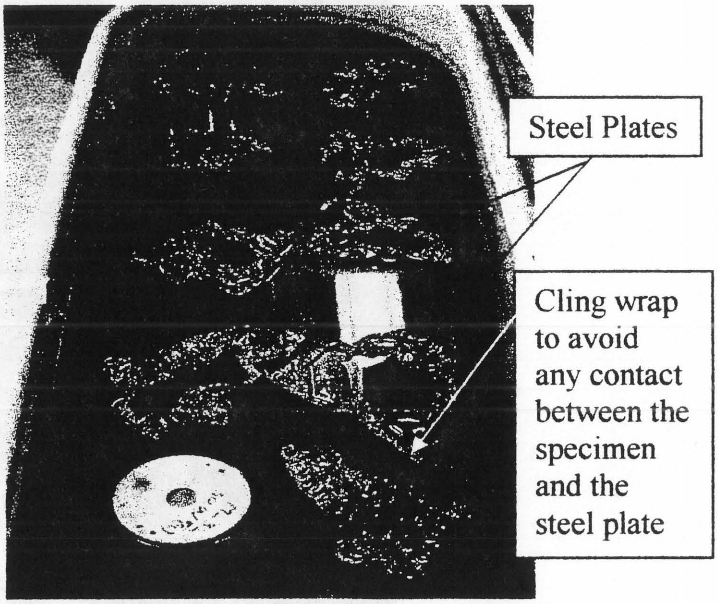


Figure 3-12 Photograph Showing Wetting of Test Samples in a Water Bath

Figure 3-13 Typical Failure of Lime-Stabilized Soil Sample (After ASTM, 1998b)

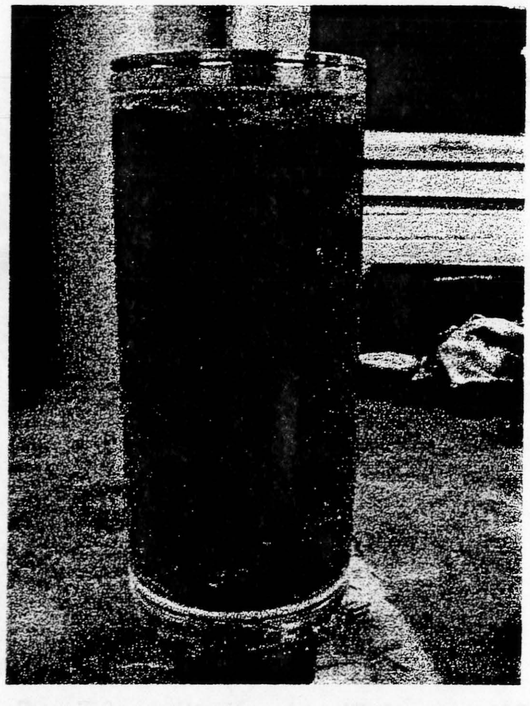


Figure 3-14 Actual Failure of CFA-Stabilized Aggregate Sample

4.1 General

This chapter is devoted to presenting the preliminary results of Phase I of this study. Resilient modulus (M_r), unconfined compressive strength (UCS), and modulus of elasticity results are presented and discussed in this chapter. Emphasis is placed on evaluating the effect of CFA stabilization, curing time, and freeze-thaw and wet-dry cycles on stabilized and raw Meridian aggregate. In addition, the optimum additive content (OAC) is presented and discussed in this chapter.

4.2 Effect of CFA Content

The resilient modulus was the only property used here to determine the optimum additive content of CFA. Six samples were molded with 5%, 10%, and 15% of CFA and moist cured for 28 days following the compaction process. After the desired curing time, samples were tested for resilient modulus. Results are summarized in Table 4-1 and graphically presented in Figure 4-1, as a function of deviatoric and bulk stress. The Mr values of samples stabilized with 5%, 10%, and 15% were in the ranges of 1829-2412 MPa (265-350 ksi), 2445-3740 MPa (354-542 ksi) and 3332-4447 MPa (483-645 ksi), respectively. Specimens stabilized with 5% CFA had Mr values approximately 250% higher than those of raw aggregate. For samples stabilized with 10% CFA, the Mr values were approximately 50% and 425% higher than the 5% CFA-stabilized and raw specimens, respectively. As the additive content increased from 10% to 15%, the Mr values increased by only 20%. Thus, as expected, the Mr values of Meridian aggregate increases as the CFA content increases. Even a relatively small amount (5%) of CFA was found to increase the Mr values quite significantly. The rate of increase was reduced with higher amounts of CFA. The difference between the Mr values of 10% CFA-stabilized specimens and 5% CFA-stabilized specimens is much higher than the corresponding difference in Mr values between the 15% CFA and 10% CFA-stabilized specimens.

4.3 Effect of Curing Time

Effectiveness of chemical stabilization depends on pozzolanic reactions among the aggregate, stabilizing agent and water. In addition, these reactions are time-dependent (Zaman et al. 1998; Van Til et al., 1972). The 3-day or 7-day strength is considered the early strength gain, whereas the 28-day strength is usually considered the standard strength, and the 90-day strength is regarded as the extra strength development for long-term utilization. The increase in pozzolanic reactions and curing time causes an increase in unconfined compressive strength (UCS) and resilient modulus (Mr).

In the current study, the effect of curing time was investigated on Meridian aggregate stabilized with 10% CFA and cured for 3, 28, and 90 days. Results are summarized in Table 4-2 and illustrated in Figure 4-2. It is seen that the Mr values of specimens stabilized with 10% CFA increase with increasing curing time. For example, the Mr values of 3-day cured specimens were approximately 280% higher than the raw aggregate. However, the Mr values of 28-day cured samples were only 40% higher than the 3-day cured samples and 425% higher than that of the raw specimen. In addition, the resilient modulus values increased only slightly as the curing time increased form 28 to 90 days. The Mr values of 90-day cured samples were approximately 25% higher than the 28-day cured samples and ranged between 3470-4447 MPa (502-645 ksi).

From these results, it is evident that the resilient modulus of CFA-stabilized samples is time-dependent. This is due to fact that the cementitious reactions with the aggregate mix and the existence of moisture increases as the curing time increases, which improves the quality and properties of stabilized aggregate. 28-day curing time is considered sufficient for a significant strength gain of CFA-stabilized aggregate base; periods longer than 28 days did not cause any significant increase in Mr values.

4.4 Effect of Freeze-Thaw and Wet-Dry Cycles

The effect of F-T/W-D cycles was examined on raw and stabilized specimens. Specimens were subjected to a number of F-T or W-D cycles before testing them for Mr and/or UCS. F-T specimens were tested after the thawing period and W-D samples were tested at the end of the wetting period. Both thawing and wetting are considered the worst situations, during the service life of a pavement.

4.4.1 Unstabilized Aggregate (Raw Aggregate)

The Mr test was the only measurement used to identify the effect of F-T and W-D cycles on raw Meridian aggregate. Samples were compacted and placed in a humidity room for three days before being subjected to F-T/W-D cycles, as shown in Figure 3-6. The number of F-T cycles was 0, 4, 12, and 30; however, W-D samples were subjected only to one cycle, because samples failed during the Mr tests. The results for F-T samples are summarized in Table 4-3 and graphically presented in Figure 4-3. It is seen that the resilient modulus values decrease as the number of F-T cycles increase. The resilient modulus values of samples subjected to 4, 12, and 30 cycles of freezing and thawing were approximately 5%, 15%, and 20% lower than the Mr values of samples without subjected to any F-T cycles. These values ranged between 449-662 MPa (65-96 ksi), 384-577 MPa (56-84 ksi), and 395-529 MPa (57-77 ksi), respectively. Apparently, the effect of F-T cycles on raw aggregate is moisture-dependent and also is a function of sample porosity. During the freezing phase water freezes and expands inside the sample voids, whereas the thawing phase involves melting of the ice crystals. The deleterious effects of F-T cycles on raw aggregate samples can be summarized as follows: (1) If there are not enough voids to let the water particle expand without causing any major disturbances to aggregate structure, the F-T cycles will have a major impact on the sample, (2) if the amount of water is large or the sample is saturated, the effect of F-T cycles will have a significant influence on its properties, and (3) If both points (1) and (2) are not applicable, it is expected that F-T cycles will not have any major influences on the properties of raw specimens. The membranes around the specimens were not removed while subjecting the specimens to F-T cycles. This method, did not allow the migration of moisture to the specimens due to high humidity, and the moisture content were almost constant with the number of cycles.

It required a lot of effort to conduct a resilient modulus test on raw aggregate subjected to one cycle of wetting/drying. Four samples were molded and placed in a water bath without any membrane to examine the effect of W-D cycles on the stability of these samples. After a period of less than 24 hours, all the samples collapsed, as shown in Figure 4-4. As a result, the resilient modulus test could not be conducted. An additional two samples were then prepared, and placed in a water bath. But this time the membranes were not removed, as shown in Figure 4-5. After 24 hours, samples were tested. However, both tests were abandoned after sequence number two, since the permanent deformations exceeded 5% of initial sample heights. Please note that external LVDT's, having a stroke length of 19.05 mm (0.75 in), were used only for this case. The increase in moisture content in samples, after being immersed in water, helped reduce the modulus and the strength of samples. The associated failed samples are shown in Figure 4-6 and the results are graphically presented in Figure 4-7. The resilient modulus values had an average value of 250 MPa (35 ksi) at a deviator stress of 69 kPa (10 psi).

4.4.2 Stabilized Aggregate with Class C Fly Ash

Mr and UCS tests were used as an indicator to evaluate the influence of F-T and W-D cycles on Meridian aggregate stabilized with 10% CFA and cured for 3 days and 28 days. Resilient modulus tests were performed on two different sets of samples, referred here as "Same Sample" and "Different Samples". Same samples (SS) were the samples that were subjected to a certain number of F-T cycles, tested for Mr, and then tested for UCS. Different samples (DS) were used for Mr testing after subjecting them to multiple sequences of F-T and W-D cycles. The numbers of F-T/W-D cycles subjected to SS and DS were 0, 4, 12, 30, and 60 cycles and 0, 4, 12, and 30 cycles, respectively. The zero cycle represents cured specimens that are not subjected to any F-T or W-D cycles.

4.4.2.1 Effect of F-T Cycles on Resilient Modulus of Same Samples

Results given in Table 4-4 show that the resilient modulus values of 28-day cured specimens increase as the number of F-T cycles increase up to a certain number, beyond which the resilient modulus exhibits a decrease. For example, the resilient modulus values of samples cured for 28 days and subjected to 12 F-T cycles were approximately 25% higher than the Mr values of samples without F-T cycles. These values were between 3623 and 4350 MPa (525-630 ksi). The resilient modulus values of samples subjected to 30 and 60 cycles were lower than the Mr values of samples subjected to 12 cycles, and ranging between 3136-4105 MPa (454-596 ksi) and 3111-3807 MPa (451-552 ksi), respectively. It seems that, cementitious and pozzolanic reactions occurred as F-T action increased up to 12 cycles causing an increase in Mr values. After 30 cycles, on the other hand, almost no pozzolanic activities were taking place and the effect of F-T cycles causes a decrease in Mr values.

The effects of F-T cycles on 3-day cured samples are summarized in Table 4-5. It is seen that the modulus increases as the freezing and thawing cycles reach 30. For example, the Mr values of samples subjected to 12 and 30 F-T cycles were higher than samples without F-T cycles and were in the ranges of 3315-3804 MPa (481-552 ksi) and 3609-4916 MPa (523-712 ksi), respectively. At 60 cycles, however, the Mr values were slightly lower, approximately 15%, than the resilient modulus of samples subjected to 30 cycles, and ranging between 3171-3638 MPa (460-527 ksi). Apparently, pozzolanic activities continue to occur and cause an increase in Mr values, until a reduction in Mr occurred.

4.4.2.2 Effect of W-D Cycles on Resilient Modulus of Same Samples

Wet-Dry cycles had the same qualitative effects on the resilient modulus values of stabilized samples. The Mr values increased as the W-D cycles increased up to a certain number, beyond which, the Mr values decreased. For example, the Mr values of 28-day cured samples subjected to 12 W-D cycles were approximately 15% higher than the resilient modulus values of samples cured for 28 days and subjected to no W-D cycle. Beyond 12 cycles, the resilient modulus started to decrease and reached a lower value ranging between 2395-3559 MPa (347-516 ksi), at 60 cycles. The increase of moisture content in samples, after being immersed in water, helped the cementation and pozzolanic reactions to occur and cause an increase in Mr values as W-D cycles increased up to 12. Results are well illustrated in Table 4-6.

As for 3-day cured samples, the resilient modulus increases as the W-D cycles increase up to 30 and decrease as the number reached 60 cycles, as listed in Table 4-7.

Specimens cured for 3 days cured samples subjected to 30 W-D cycles had Mr values between 2961 and 4160 MPa (429-604 ksi). At 60 cycles, the resilient modulus values were approximately 25% lower than those subjected to 30 cycles; but 20% higher compared with the corresponding Mr values of samples without any W-D cycles. The cementations and pozzolanic were enhanced due to W-D cycles until a reduction in Mr values occurred.

4.4.2.3 Effect of F-T/W-D on Resilient Modulus of Different Samples

The Mr values versus the stress levels of 28-day cured samples subjected to F-T cycles are given in Table 4-8. The Mr values increased as the number of F-T cycles reached 12 cycles and decreased at 30 cycles. The Mr values of samples subjected to 12 cycles were approximately 25% higher than the value for specimens without any F-T cycles, and ranging between 3452 and 4377 MPa (500-634 ksi). However, samples subjected to 30 cycles had Mr values 7% lower than samples subjected to 12 cycles, but approximately 15% higher than the samples without any F-T cycles. The Mr values of 3-day cured samples subjected to F-T cycles exhibited an increase as the number of cycles increased up to 30 cycles, as illustrated in Table 4-9. The resilient modulus of samples subjected to 12 and 30 F-T cycles were approximately 60% and 80%, respectively, higher than those without any such cycles, and ranging between 3260-4100 MPa (473-594 ksi), and 3796-4819 (550-698 ksi). In addition, it is observed that the difference between samples subjected to 12 cycles and samples without any cycles is much higher than the difference between samples subjected to 12 and 30 cycles.

As for W-D samples, results of both 28- and 3-day cured samples are summarized in Tables 4-10 and 4-11, respectively. Mr values exhibited an increase and then a decrease. As an example, the Mr values of 28-day cured samples subjected to 12 cycles of wetting and drying were around 20% higher than samples without W-D cycles and were in the range of 3202-4350MPa (464-630 ksi). At 30 cycles, the Mr values decreased and varied between 2313-3685 MPa (335-534 ksi). As for the 3-day cured samples, the Mr values exhibited an increase as the number of W-D cycles reached 12 cycles, beyond that it started to reduce slightly and reached a value between 3061-3904 MPa (444-566 ksi), at 30 cycles.

No tests were performed on samples subjected to 60 cycles. Overall, the trend lines for resilient modulus of DS specimens are quite consistent with the Mr results for SS specimens as the number of F-T/W-D cycles increases. A comparison between SS and DS samples are discussed in the following.

4.4.2.4 Relative Comparison Between Same Samples and Different Samples

Figure 4-8 shows a comparison of Mr values between same and different samples for 28-day cured specimens subjected to F-T cycles. A similar comparison for the 3-day cured specimen is shown in Figure 4-9. A corresponding comparison for W-D cycles is presented in Figures 4-10 and 4-11. Although the level of scatter in Mr values for the W-D samples is somewhat higher than the F-T specimens, it is within a reasonable range. Therefore, it is concluded that same specimens can be used to examine the effects of F-T and W-D cycles on the resilient modulus of CFA-stabilized samples, as long as the number of Mr tests are relatively low.

4.4.3 Unconfined Compressive Strength

The UCS tests were performed on samples subjected to Mr tests, called Mr samples (MrS), and on samples that were not tested for Mr, called virgin samples (VS). Both MrS and VS samples were subjected to 0, 4, 12, and 30 cycles of F-T/W-D action, zero cycle being the reference samples that are not subjected to any F-T/W-D action.

Results are summarized in Table 4-12 and graphically illustrated in Figures 4-12 and 4-13. It is noted that the UCS of samples subjected to F-T or W-D cycles are higher than the values for specimens not subjected to any cycles. The UCS values in all cases exhibited an increase as the number of F-T or W-D cycles increased up to 30. As an example, the UCS values of 28-day cured Mr samples subjected to 0, 4, 12 and 30 F-T cycles were 2555 kPa (371 psi), 2668 kPa (387 psi), 2987 kPa (433 psi) and 3059 kPa (443 psi), respectively. Also, the UCS for 3-day cured MrS subjected to 4, 12, and 30 W-D cycles were approximately 63%, 130%, and 130%, respectively, higher than those for samples without any W-D cycles. The average values were 3205 kPa (465 psi), 4525 kPa (656 psi), and 4531 kPa (657 psi), respectively.

As seen from Figures 4-12 and 4-13, the UCS values of Mr samples exhibited slightly higher values than those of virgin samples. It appears that Mr tests had a slight preloading effect that made the samples stronger than their virgin counterparts, which is consistent with the results presented by Zhu (1998). In addition, laboratory observations from the present study revealed water at the sample periphery after performing the Mr test and prior to UCS test. Thus, a decrease in moisture may occur, which contributes to higher UCS values.

4.4.4 Modulus of Elasticity

Modulus of elasticity or elastic modulus (E) is a material property determined from the stress-strain data obtained from a UCS test or other tests. It is defined as the initial slope of the stress-strain curve. The E values obtained from samples subjected to F-T/W-D cycles are listed in Table 4-12 and graphically presented in Figures 4-14 and 4-15. Similar to UCS, the modulus of elasticity showed the same trend line. The modulus values increased as the number of F-T and W-D cycles increased up to 30 cycles. Beyond 30 cycles no data are available. For example, the E values of 3-day cured samples subjected to 4, 12, and 30 W-D cycles were approximately 135%, 170%, and 200% higher than the corresponding values for specimens not subjected to any F-T or W-D cycles. Also, it is observed that the modulus of W-D samples is higher than F-T samples.

4.5 Determination of Criteria for Defining the Tests Matrix for Phase II

In view of Phase I results and observations, based on author's experience, and other results from Zaman et al. (1998), the following criteria will be used to define the test Matrix for Phase II of this study.

1) The optimum additive content (OAC) will be used to evaluate the effect of F-T and W-D cycles on stabilized aggregate bases. OAC of each aggregate type and stabilizing agent are summarized in Table 4-13.

2) Same specimens scheme will be used to evaluate the effect of durability.

3) Membranes around the specimens will be removed while subjecting them to F-T cycles.

4) One curing time will be used, namely, 28 days.

5) Portland cement will be only used to stabilize Meridian aggregate.

6) Combination of CFA and PC will not be used to stabilize aggregate, because CFA is a self-cementing stabilizing agent.

Table 4-1 Mr Values of Raw and Stabilized Meridian Aggregate with 5%, 10%, and 15% of CFA

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0% CFA		5% CFA		10% CFA		15% CFA	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	622	90	2007	291	3049	443	3332	484
138	20	138	20	28	4	636	92	2186	317	3150	457	3689	535
138	20	208	30	28	4	680	99	2200	319	3611	524	3812	553
138	20	277	40	28	4	711	103	2412	350	3740	543	4029	585
104	15	69	10	28	4	601	87	2015	292	2953	429	3390	492
104	15	138	20	28	4	639	93	2013	292	3055	443	3778	548
104	15	208	30	28	4	674	98	2127	309	3369	489	3989	579
104	15	277	40	28	4	691	100	2181	316	3392	492	4005	581
69	10	69	10	28	4	530	77	2005	291	2820	409	3408	495
69	10	138	20	28	4	567	82	1972	286	2986	433	3794	551
69	10	208	30	28	4	622	90	2122	308	3301	479	3883	564
69	10	277	40	28	4	648	94	2186	317	3380	491	4447	645
35	5	69	10	28	4	479	70	1829	265	2744	398	3435	499
35	5	138	20	28	4	521	76	1988	289	2933	426	3717	539
35	5	208	30	28	4	582	85	2070	300	3279	476	3862	560
35	5	277	40	28	4	615	89	2164	314	3367	489	4327	628
0	0	69	10	28	4	470	68	1859	270	2445	355	3428	498
0	0	138	20	28	4	520	75	1999	290	2886	419	3785	549
0	0	208	30	28	4	587	85	2036	296	3257	473	3997	580
0	0	277	40	28	4	616	89	2143	311	3313	481	4125	599

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-2 Mr Values of Raw and Meridian Aggregate Stabilized with 10% CFA and Cured for 3, 28, and 90 Days

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	Raw		3-day Cured Samples		28-day Cured Samples		90-day Cured Samples	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	622	90	2230	324	3049	443	3470	504
138	20	138	20	28	4	636	92	2402	349	3150	457	3883	564
138	20	208	30	28	4	680	99	2444	355	3611	524	3971	576
138	20	277	40	28	4	711	103	2660	385	3740	543	4029	585
104	15	69	10	28	4	601	87	2239	325	2953	429	3495	507
104	15	138	20	28	4	639	93	2212	321	3055	443	3895	565
104	15	208	30	28	4	674	98	2312	336	3369	489	3989	579
104	15	277	40	28	4	691	100	2450	356	3392	492	4261	618
69	10	69	10	28	4	530	77	2179	316	2820	409	3478	505
69	10	138	20	28	4	567	82	2191	318	2986	433	3871	562
69	10	208	30	28	4	622	90	2307	335	3301	479	4003	581
69	10	277	40	28	4	648	94	2402	349	3380	491	4447	645
35	5	69	10	28	4	479	70	2010	292	2744	398	3470	504
35	5	138	20	28	4	521	76	2209	321	2933	426	3872	562
35	5	208	30	28	4	582	85	2300	334	3279	476	3981	578
35	5	277	40	28	4	615	89	2352	341	3367	489	4438	644
0	0	69	10	28	4	470	68	2021	293	2445	355	3498	508
0	0	138	20	28	4	520	75	2246	326	2886	419	3902	566
0	0	208	30	28	4	587	85	2263	328	3257	473	3997	580
0	0	277	40	28	4	616	89	2329	338	3313	481	4297	624

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-3 Mr Values of Raw Meridian Aggregate Subjected to 0, 4, 12, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycles		4 F-T cycles		12 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	622	90	532	77	506	73	417	61
138	20	138	20	28	4	636	92	620	90	532	77	460	67
138	20	208	30	28	4	680	99	662	96	557	81	505	73
138	20	277	40	28	4	711	103	646	94	558	81	521	76
104	15	69	10	28	4	601	87	509	74	449	65	398	58
104	15	138	20	28	4	639	93	574	83	493	72	458	67
104	15	208	30	28	4	674	98	629	91	553	80	497	72
104	15	277	40	28	4	691	100	645	94	577	84	528	77
69	10	69	10	28	4	530	77	482	70	438	64	395	57
69	10	138	20	28	4	567	82	540	78	487	71	449	65
69	10	208	30	28	4	622	90	611	89	525	76	505	73
69	10	277	40	28	4	648	94	655	95	575	83	529	77
35	5	69	10	28	4	479	70	475	69	403	58	401	58
35	5	138	20	28	4	521	76	539	78	457	66	435	63
35	5	208	30	28	4	582	85	601	87	522	76	492	71
35	5	277	40	28	4	615	89	637	93	547	79	529	77
0	0	69	10	28	4	470	68	449	65	384	56	410	59
0	0	138	20	28	4	520	75	527	76	454	66	441	64
0	0	208	30	28	4	587	85	591	86	512	74	497	72
0	0	277	40	28	4	616	89	624	91	541	78	513	74

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

F-T = Freeze-Thaw

Table 4-4 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 4, 12, 30, and 60 Cycles of Freezing and Thawing (Same Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		4 F-T cycles		8 F-T cycles		12 F-T cycles		30 F-T cycles		60 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2230	324	2564	372	3124	453	3367	489	3985	578	3310	480
138	20	138	20	28	4	2402	349	2682	389	3366	489	3472	504	4348	631	3433	498
138	20	208	30	28	4	2444	355	3064	445	3562	517	3577	519	4511	655	3506	509
138	20	277	40	28	4	2650	385	3282	476	3756	545	3763	546	4916	714	3638	528
104	15	69	10	28	4	2239	325	2518	365	3060	444	3329	483	3963	575	3205	465
104	15	138	20	28	4	2212	321	2548	370	3206	465	3390	492	3987	579	3398	493
104	15	208	30	28	4	2312	336	2701	392	3267	474	3667	532	4079	592	3436	499
104	15	277	40	28	4	2450	356	2980	433	3547	515	3804	552	4364	633	3570	518
69	10	69	10	28	4	2179	316	2476	359	3010	437	3350	486	3765	546	3326	483
69	10	138	20	28	4	2191	318	2545	369	3081	447	3413	495	4004	581	3352	486
69	10	208	30	28	4	2307	335	2643	384	3329	483	3602	523	4072	591	3432	498
69	10	277	40	28	4	2402	349	2786	404	3458	502	3700	537	4268	619	3551	515
35	5	69	10	28	4	2010	292	2474	359	3071	446	3315	481	3744	543	3171	460
35	5	138	20	28	4	2209	321	2532	367	3173	461	3369	489	3805	552	3337	484
35	5	208	30	28	4	2300	334	2667	387	3228	469	3530	512	3945	573	3409	495
35	5	277	40	28	4	2352	341	2745	398	3325	483	3620	525	4092	594	3544	514
0	0	69	10	28	4	2021	293	2445	355	3039	441	3359	488	3609	524	3242	471
0	0	138	20	28	4	2246	326	2505	364	3140	456	3436	499	3724	540	3305	480
0	0	208	30	28	4	2263	328	2603	378	3183	462	3605	523	3831	556	3412	495
0	0	277	40	28	4	2329	338	2689	390	3252	472	3695	536	3918	569	3533	513

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-5 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 3 Days and Subjected to 0, 4, 12, 30, and 60 Cycles of Freezing and Thawing (Same Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		4 F-T cycles		12 F-T cycles		30 F-T cycles		60 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2230	324	2564	372	3367	489	3985	578	3310	480
138	20	138	20	28	4	2402	349	2682	389	3472	504	4348	631	3433	498
138	20	208	30	28	4	2444	355	3064	445	3577	519	4511	655	3506	509
138	20	277	40	28	4	2650	385	3282	476	3763	546	4916	714	3638	528
104	15	69	10	28	4	2239	325	2518	365	3329	483	3963	575	3205	465
104	15	138	20	28	4	2212	321	2548	370	3390	492	3987	579	3398	493
104	15	208	30	28	4	2312	336	2701	392	3667	532	4079	592	3436	499
104	15	277	40	28	4	2450	356	2980	433	3804	552	4364	633	3570	518
69	10	69	10	28	4	2179	316	2476	359	3350	486	3765	546	3326	483
69	10	138	20	28	4	2191	318	2545	369	3413	495	4004	581	3352	486
69	10	208	30	28	4	2307	335	2643	384	3602	523	4072	591	3432	498
69	10	277	40	28	4	2402	349	2786	404	3700	537	4268	619	3551	515
35	5	69	10	28	4	2010	292	2474	359	3315	481	3744	543	3171	460
35	5	138	20	28	4	2209	321	2532	367	3369	489	3805	552	3337	484
35	5	208	30	28	4	2300	334	2667	387	3530	512	3945	573	3409	495
35	5	277	40	28	4	2352	341	2745	398	3620	525	4092	594	3544	514
0	0	69	10	28	4	2021	293	2445	355	3359	488	3609	524	3242	471
0	0	138	20	28	4	2246	326	2505	364	3436	499	3724	540	3305	480
0	0	208	30	28	4	2263	328	2603	378	3605	523	3831	556	3412	495
0	0	277	40	28	4	2329	338	2689	390	3695	536	3918	569	3533	513

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-6 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 4, 12, 30, and 60 Cycles of Wetting and Drying (Same Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		4 W-D cycles		12 W-D cycles		30 W-D cycles		60 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3049	443	3400	493	3410	495	2848	413	2887	419
138	20	138	20	28	4	3150	457	3491	507	3523	511	3040	441	2808	408
138	20	208	30	28	4	3611	524	3500	508	3911	568	3448	500	3224	468
138	20	277	40	28	4	3740	543	3950	573	4293	623	3583	520	3320	482
104	15	69	10	28	4	2953	429	3100	450	3303	479	2724	395	2805	407
104	15	138	20	28	4	3055	443	3144	456	3416	496	2870	417	2813	408
104	15	208	30	28	4	3369	489	3341	485	3822	555	3206	465	3167	460
104	15	277	40	28	4	3392	492	3941	572	4236	615	3495	507	3559	517
69	10	69	10	28	4	2820	409	3078	447	3154	458	2690	390	2657	386
69	10	138	20	28	4	2986	433	3256	473	3339	485	2749	399	2723	395
69	10	208	30	28	4	3301	479	3290	477	3740	543	3086	448	3089	448
69	10	277	40	28	4	3380	491	3708	538	4205	610	3422	497	3283	477
35	5	69	10	28	4	2744	398	3002	436	3069	445	2656	386	2521	366
35	5	138	20	28	4	2933	426	3158	458	3281	476	2663	387	2614	379
35	5	208	30	28	4	3279	476	3264	474	3681	534	3022	439	3032	440
35	5	277	40	28	4	3367	489	3426	497	4151	602	3349	486	3343	485
0	0	69	10	28	4	2445	355	2650	385	3008	437	2605	378	2395	348
0	0	138	20	28	4	2886	419	2745	398	3228	469	2684	390	2484	360
0	0	208	30	28	4	3257	473	2983	433	3633	527	2986	433	2880	418
0	0	277	40	28	4	3313	481	3629	527	4101	595	3342	485	3176	461

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-7 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 3 Days and Subjected to 0, 4, 12, 30, and 60 Cycles of Wetting and Drying (Same Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		4 W-D cycle		12 W-D cycles		30 W-D cycles		60 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2230	324	2854	414	3263	474	3429	498	2640	383
138	20	138	20	28	4	2402	349	3026	439	3497	508	3554	516	2878	418
138	20	208	30	28	4	2444	355	3057	444	3802	552	3750	544	3137	455
138	20	277	40	28	4	2650	385	3083	447	3883	564	4160	604	3225	468
104	15	69	10	28	4	2239	325	2591	376	3136	455	3305	480	2442	354
104	15	138	20	28	4	2212	321	2861	415	3449	501	3422	497	2691	391
104	15	208	30	28	4	2312	336	2992	434	3554	516	3746	544	3030	440
104	15	277	40	28	4	2450	356	3002	436	3720	540	4049	588	3109	451
69	10	69	10	28	4	2179	316	2604	378	3090	448	3250	472	2328	338
69	10	138	20	28	4	2191	318	2805	407	3420	496	3346	486	2595	377
69	10	208	30	28	4	2307	335	2918	424	3445	500	3641	528	2944	427
69	10	277	40	28	4	2402	349	2975	432	3603	523	3968	576	3093	449
35	5	69	10	28	4	2010	292	2604	378	2908	422	3300	479	2255	327
35	5	138	20	28	4	2209	321	2732	396	3242	471	3288	477	2528	367
35	5	208	30	28	4	2300	334	2879	418	3381	491	3591	521	2891	420
35	5	277	40	28	4	2352	341	2826	410	3538	514	3889	564	3003	436
0	0	69	10	28	4	2021	293	2560	371	3196	464	2961	430	2155	313
0	0	138	20	28	4	2246	326	2706	393	3398	493	3378	490	2435	353
0	0	208	30	28	4	2263	328	2874	417	3468	503	3639	528	2786	404
0	0	277	40	28	4	2329	338	2845	413	3526	512	3667	532	2921	424
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa															
θ = Bulk Stress															
σ_d = Deviator Stress															
σ_3 = Confining Pressure															
σ_s = Seating Pressure															
Mr = Resilient Modulus															

Table 4-8 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 4, 12, and 30 Cycles of Freezing and Thawing (Different Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		4 F-T cycles		12 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3049	443	3097	450	3758	545	3537	513
138	20	138	20	28	4	3150	457	3141	456	3952	574	3711	539
138	20	208	30	28	4	3611	524	3203	465	3974	577	3784	549
138	20	277	40	28	4	3740	543	3544	514	4377	635	3989	579
104	15	69	10	28	4	2953	429	3072	446	3723	540	3360	488
104	15	138	20	28	4	3055	443	3103	450	3990	579	3637	528
104	15	208	30	28	4	3369	489	3133	455	4142	601	3709	538
104	15	277	40	28	4	3392	492	3439	499	4201	610	3958	574
69	10	69	10	28	4	2820	409	3023	439	3576	519	3111	452
69	10	138	20	28	4	2986	433	3056	444	3629	527	3300	479
69	10	208	30	28	4	3301	479	3077	447	3754	545	3659	531
69	10	277	40	28	4	3380	491	3363	488	3911	568	3872	562
35	5	69	10	28	4	2744	398	2828	410	3452	501	0	0
35	5	138	20	28	4	2933	426	3027	439	4057	589	0	0
35	5	208	30	28	4	3279	476	3041	441	4172	605	0	0
35	5	277	40	28	4	3367	489	3286	477	4213	611	0	0
0	0	69	10	28	4	2445	355	2810	408	3516	510	0	0
0	0	138	20	28	4	2886	419	2951	428	3566	518	0	0
0	0	208	30	28	4	3257	473	2990	434	3655	531	0	0
0	0	277	40	28	4	3313	481	3225	468	3839	557	0	0
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa													
θ = Bulk Stress													
σ_d = Deviator Stress													
σ_3 = Confining Pressure													
σ_s = Seating Pressure													
Mr = Resilient Modulus													

Table 4-9 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 3 Days and Subjected to 0, 4, 12, and 30 Cycles of Freezing and Thawing (Different Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		4 F-T cycles		12 F-T cycles		30 F-T cycles	
						Mr_a (MPa)	Mr_a (ksi)	Mr_a (MPa)	Mr_a (ksi)	Mr_a (MPa)	Mr_a (ksi)	Mr_a (MPa)	Mr_a (ksi)
138	20	69	10	28	4	2230	324	2496	362	3760	546	4056	589
138	20	138	20	28	4	2402	349	3032	440	3868	561	4295	623
138	20	208	30	28	4	2444	355	3238	470	3920	569	4495	652
138	20	277	40	28	4	2650	385	3334	484	4100	595	4819	699
104	15	69	10	28	4	2239	325	2698	392	3693	536	3932	571
104	15	138	20	28	4	2212	321	2725	395	3761	546	4015	583
104	15	208	30	28	4	2312	336	2891	420	3775	548	4212	611
104	15	277	40	28	4	2450	356	2961	430	4002	581	4376	635
69	10	69	10	28	4	2179	316	2522	366	3547	515	3892	565
69	10	138	20	28	4	2191	318	2628	381	3647	529	4025	584
69	10	208	30	28	4	2307	335	2686	390	3726	541	4163	604
69	10	277	40	28	4	2402	349	2919	424	3780	549	4219	612
35	5	69	10	28	4	2010	292	2484	360	3486	506	3796	551
35	5	138	20	28	4	2209	321	2599	377	3531	512	3892	565
35	5	208	30	28	4	2300	334	2648	384	3596	522	4094	594
35	5	277	40	28	4	2352	341	2887	419	3625	526	4170	605
0	0	69	10	28	4	2021	293	2294	333	3260	473	N/A	N/A
0	0	138	20	28	4	2246	326	2461	357	3378	490	N/A	N/A
0	0	208	30	28	4	2263	328	2646	384	3371	489	N/A	N/A
0	0	277	40	28	4	2329	338	2891	420	3507	509	N/A	N/A

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-10 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 4, 12, and 30 Cycles of Wetting and Drying (Different Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		4 W-D cycles		12 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3049	443	3250	472	3900	566	3197	464
138	20	138	20	28	4	3150	457	3302	479	4090	594	3379	490
138	20	208	30	28	4	3611	524	3456	502	4205	610	3398	493
138	20	277	40	28	4	3740	543	3462	502	4350	631	3685	535
104	15	69	10	28	4	2953	429	3150	457	3600	522	2991	434
104	15	138	20	28	4	3055	443	3242	471	3771	547	2736	397
104	15	208	30	28	4	3369	489	3308	480	3793	551	2967	431
104	15	277	40	28	4	3392	492	3427	497	3979	578	3161	459
69	10	69	10	28	4	2820	409	3102	450	3540	514	2374	345
69	10	138	20	28	4	2986	433	3236	470	3607	523	2500	363
69	10	208	30	28	4	3301	479	3250	472	3721	540	2764	401
69	10	277	40	28	4	3380	491	3466	503	3930	570	3025	439
35	5	69	10	28	4	2744	398	2972	431	3275	475	2313	336
35	5	138	20	28	4	2933	426	3153	458	3466	503	2985	433
35	5	208	30	28	4	3279	476	3174	461	3610	524	3141	456
35	5	277	40	28	4	3367	489	3414	496	3890	565	3351	486
0	0	69	10	28	4	2445	355	2870	417	3202	465	0	0
0	0	138	20	28	4	2886	419	3122	453	3376	490	0	0
0	0	208	30	28	4	3257	473	3147	457	3563	517	0	0
0	0	277	40	28	4	3313	481	3283	477	3844	558	0	0

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-11 Mr Values of CFA-Stabilized Meridian Aggregate Cured for 3 Days and Subjected to 0, 4, 12, and 30 Cycles of Wetting and Drying (Different Samples)

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		4 W-D cycles		12 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2230	324	2820	409	3125	454	3305	480
138	20	138	20	28	4	2402	349	2880	418	3289	477	3724	540
138	20	208	30	28	4	2444	355	2987	433	3651	530	3775	548
138	20	277	40	28	4	2650	385	3179	461	3776	548	3904	567
104	15	69	10	28	4	2239	325	2926	425	3088	448	3274	475
104	15	138	20	28	4	2212	321	2688	390	3245	471	3584	520
104	15	208	30	28	4	2312	336	2834	411	3643	529	3647	529
104	15	277	40	28	4	2450	356	3061	444	3916	568	3799	551
69	10	69	10	28	4	2179	316	2652	385	3084	448	3203	465
69	10	138	20	28	4	2191	318	2569	373	3215	467	3496	507
69	10	208	30	28	4	2307	335	2756	400	3529	512	3574	519
69	10	277	40	28	4	2402	349	3022	439	3847	558	3679	534
35	5	69	10	28	4	2010	292	2659	386	2977	432	3133	455
35	5	138	20	28	4	2209	321	2556	371	3091	449	3441	499
35	5	208	30	28	4	2300	334	2746	399	3451	501	3582	520
35	5	277	40	28	4	2352	341	3025	439	3791	550	3673	533
0	0	69	10	28	4	2021	293	2472	359	2899	421	3061	444
0	0	138	20	28	4	2246	326	2528	367	3013	437	3345	486
0	0	208	30	28	4	2263	328	2712	394	3343	485	3479	505
0	0	277	40	28	4	2329	338	3006	436	3692	536	3551	515

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 4-12 UCS Values of Virgin and Mr Samples of CFA-Stabilized Meridian Aggregate Cured for 3 Days and 28 Days and Subjected to 0, 4, 12, and 30 Cycles of Freezing-Thawing and Wetting-Drying

Curing Time (Days)	Type of Cycles	Mr Samples			Virgin Samples		
		No. cycles	Uc, kPa (kPa)	E (MPa)	No. cycles	Uc, kPa (kPa)	E (MPa)
28	F-T	0	2555	1562	0	2555	1562
		4	2668	1579	4	2692	1548
		12	2987	1805	12	2888	1744
		30	3059	1904	30	2994	1771
28	W-D	0	2555	1562	0	2555	1562
		4	3456	2143	4	2866	2013
		12	4537	2567	12	4210	2527
		30	4896	2839	30	4662	2770
3	F-T	0	1971	839	0	1971	839
		4	2280	1448	4	2141	1351
		12	2764	1587	12	2555	1550
		30	2864	1755	30	2768	1669
3	W-D	0	1971	839	0	1971	839
		4	3205	1760	4	3002	1974
		12	4525	2245	12	4234	2267
		30	4531	2493	30	4303	2489
1 psi = 6.89 kPa							

Table 4-13 Optimum Additive Content of Stabilized Aggregates

Additive type	Agrgegate Type	OAC
CKD	Meridian	15
CFA	Meridian	10
FBA	Meridian	10
PC	Meridian	3
CKD	Richard Spur	15
CFA	Richard Spur	10
FBA	Richard Spur	10
CKD	Sawyer	15
CFA	Sawyer	10
FBA	Sawyer	10
CKD	Hanson	15
FBA	Hanson	10
OAC; Optimum Additive Content		

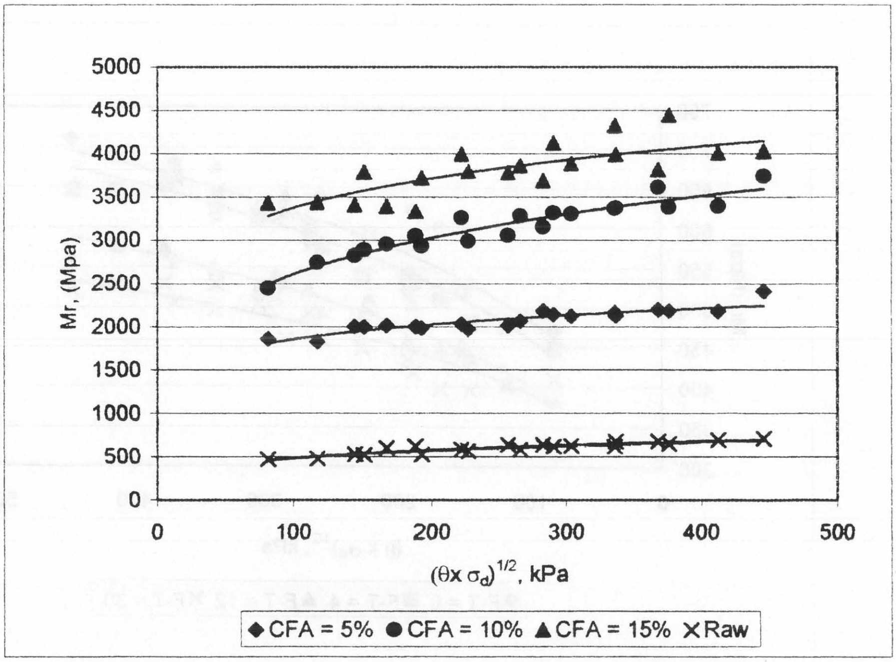


Figure 4-1 Mr Values vs the Square Root of Bulk Stress and Deviator Stress of Raw Aggregate and Stabilized Aggregate with 5%, 10% and 15% CFA and Cured for 28 Days

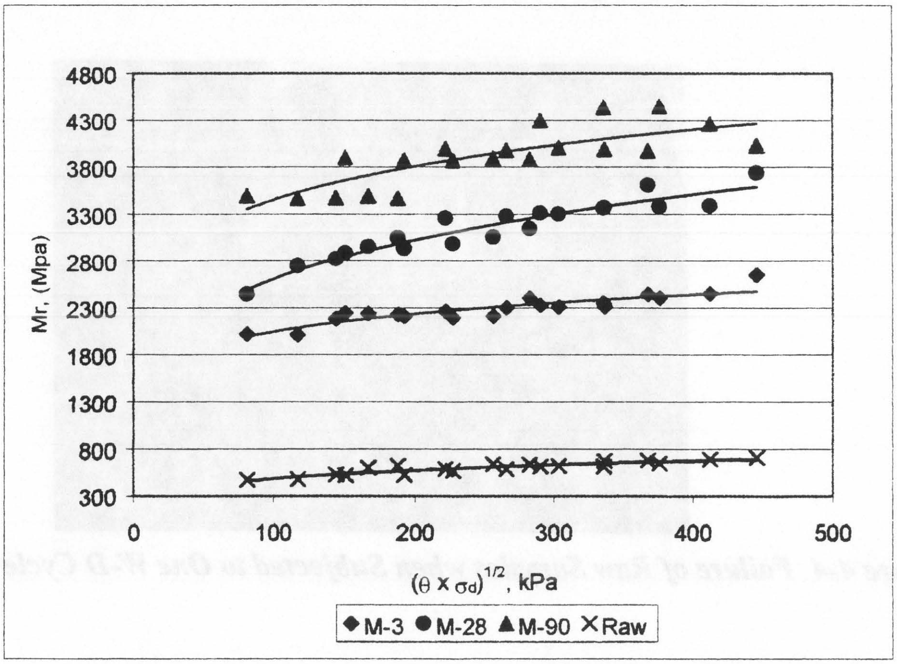


Figure 4-2 Mr Values vs the Square Root of Bulk Stress and Deviator Stress of Raw Aggregate and Aggregate Stabilized with 10% CFA and Cured for 3, 28, and 90 Days

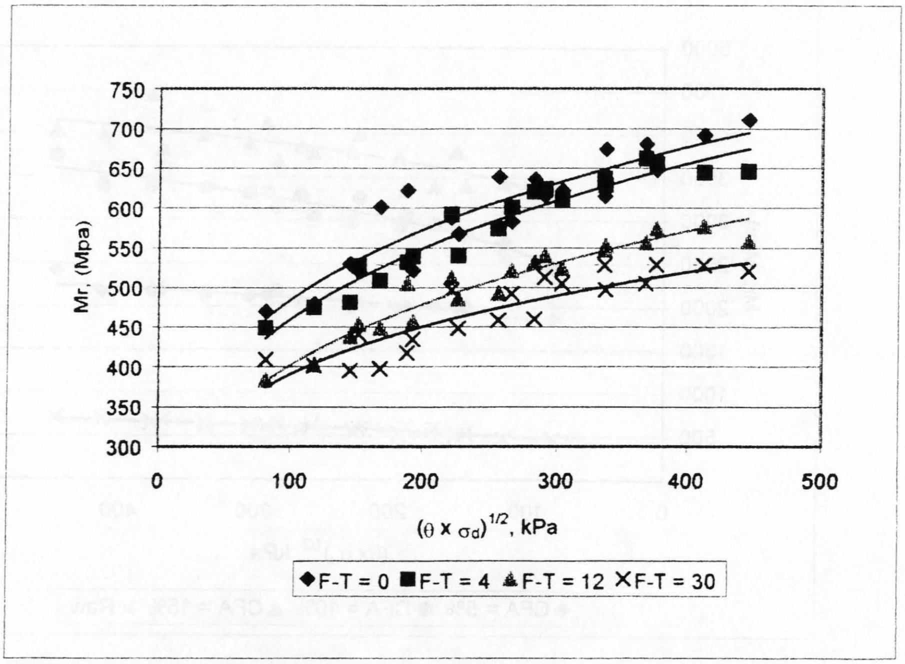


Figure 4-3 Mr Values vs the Square Root of Bulk Stress and Deviator Stress of Unstabilized Specimens Subjected to 0, 4, 12, and 30 F-T Cycles

Figure 4-4 Failure of Raw Samples when Subjected to One W-D Cycle

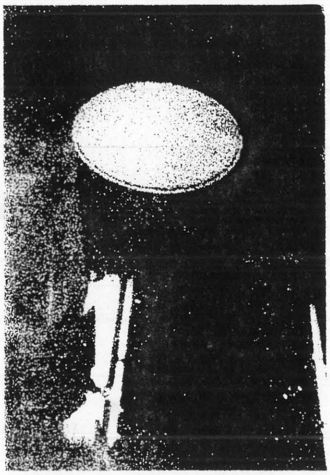


Figure 4-5 Raw Sample with Membrane Subjected to W-D Cycle

Figure 4-6 Failure of Raw Sample after being Subjected to One W-D Cycle and Tested for Mr

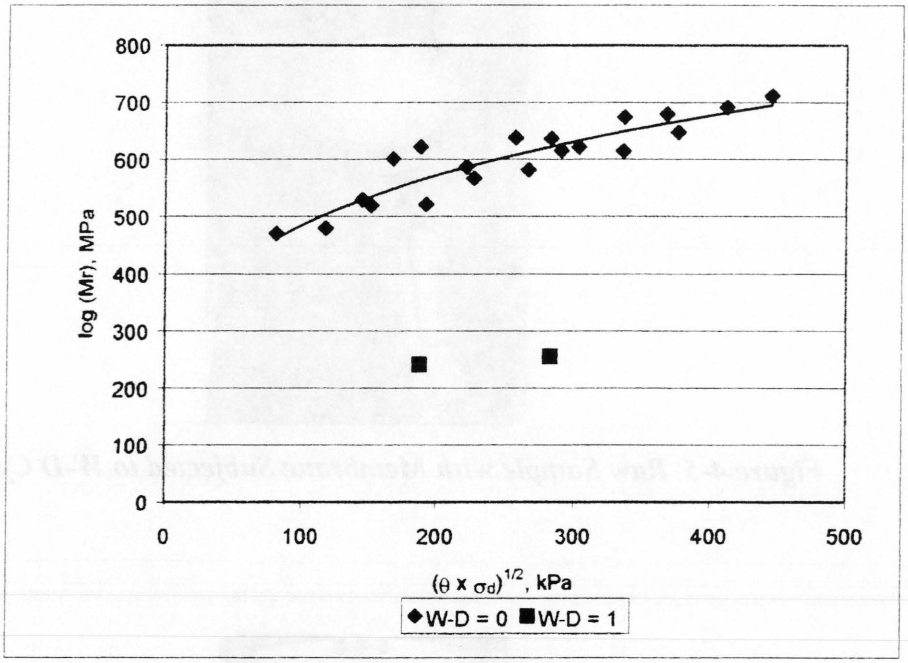


Figure 4-7 Mr Values vs the Square Root of Bulk Stress and Deviator Stress of Unstabilized Aggregate Subjected to Zero, and One Cycle of Wetting and Drying

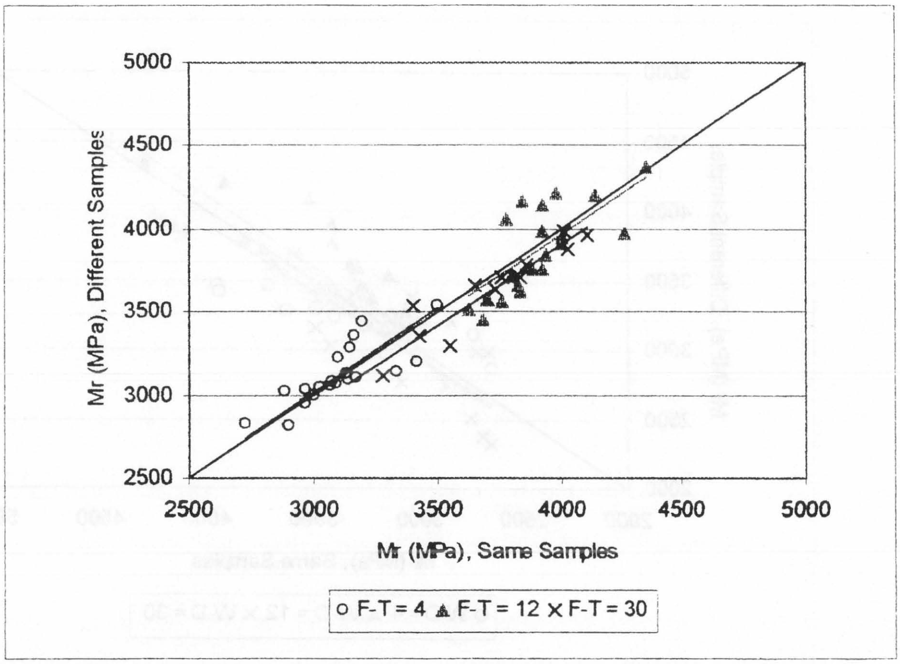


Figure 4-8 Mr Values of Same Samples vs Mr Values of Different Samples Cured for 28 Days and Subjected to F-T Cycles

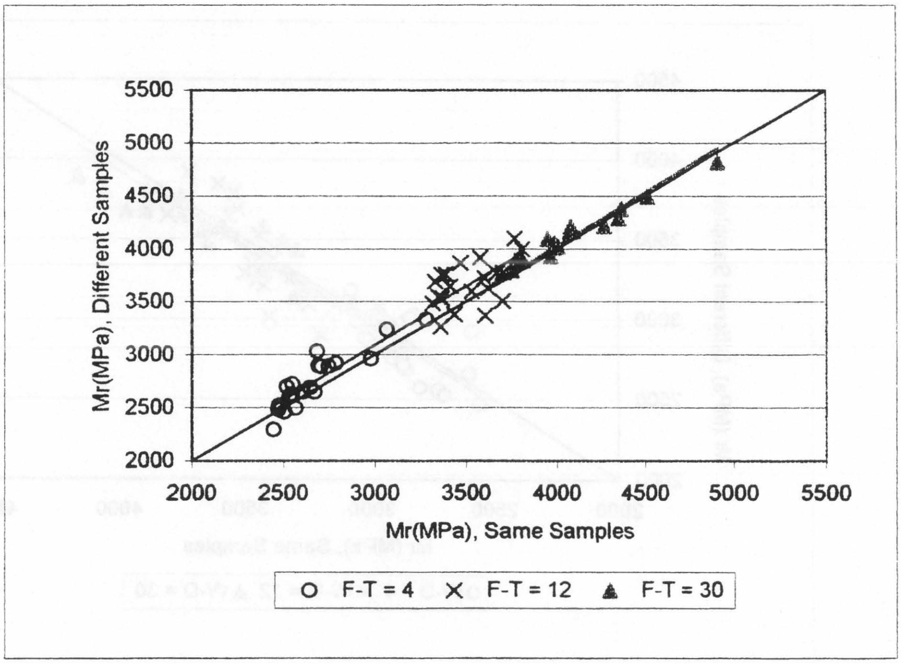


Figure 4-9 Mr Values of Same Samples vs Mr Values of Different Samples Cured for 3 Days and Subjected to F-T Cycles

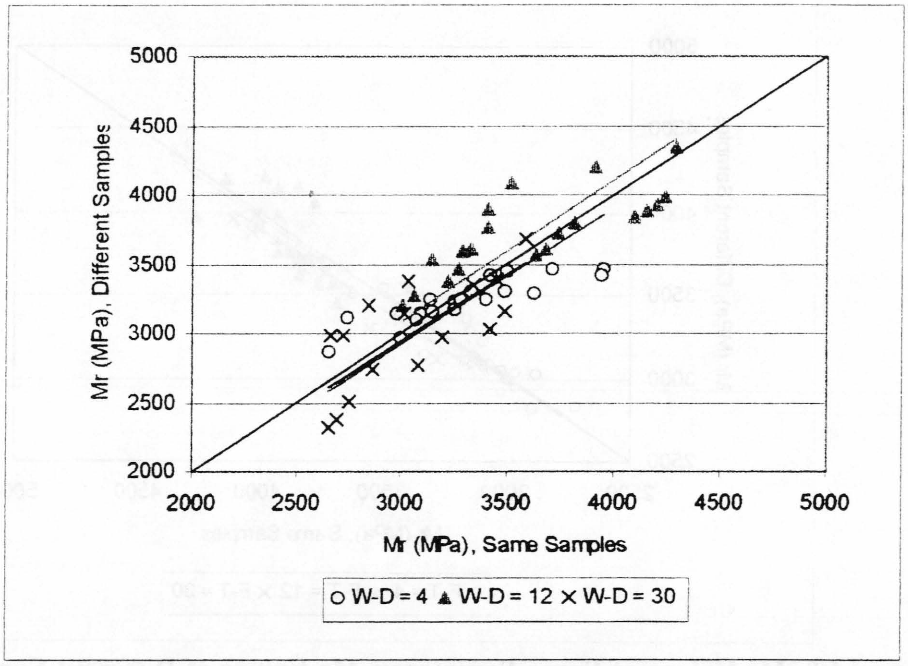


Figure 4-10 Mr Values of Same Samples vs Mr Values of Different Samples Cured for 28 Days and Subjected to W-D Cycles

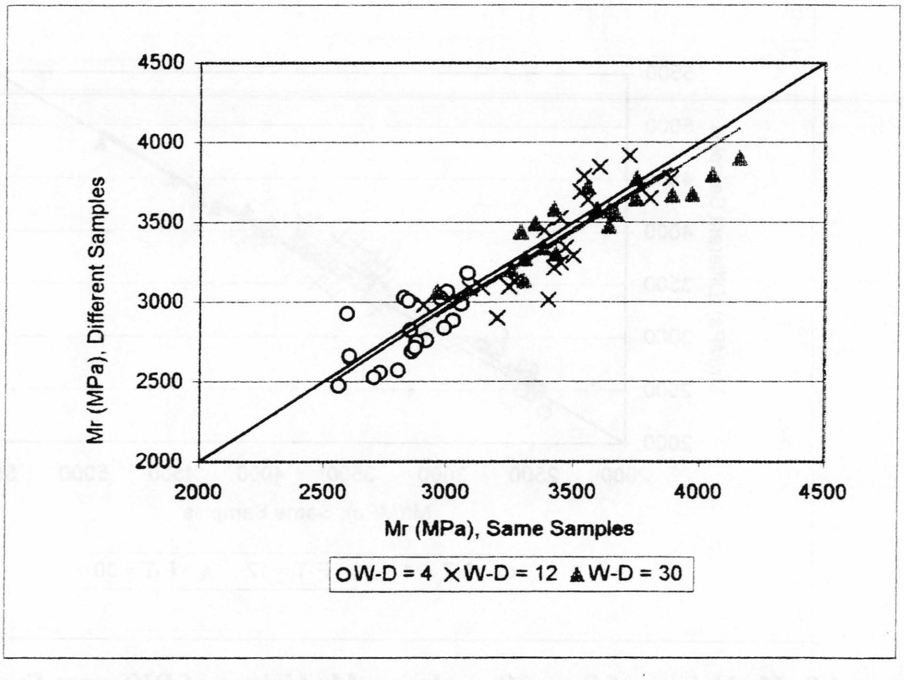


Figure 4-11 Mr Values of Same Samples vs Mr Values of Different Samples Cured for 3 Days and Subjected to W-D Cycles

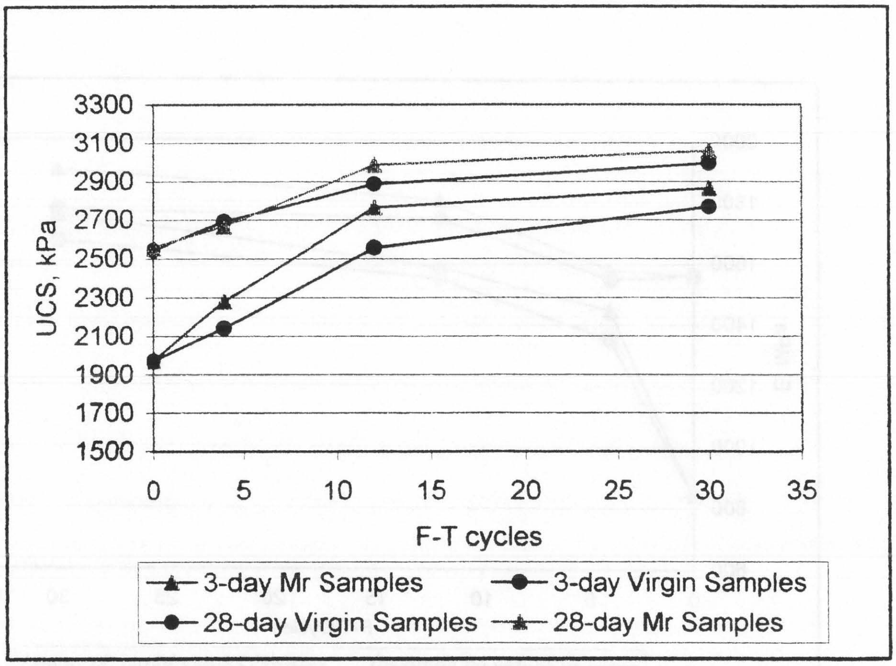


Figure 4-12 UCS Values of Virgin and Mr Samples of 3-Day and 28-Day Cured Samples Subjected to F-T Cycles

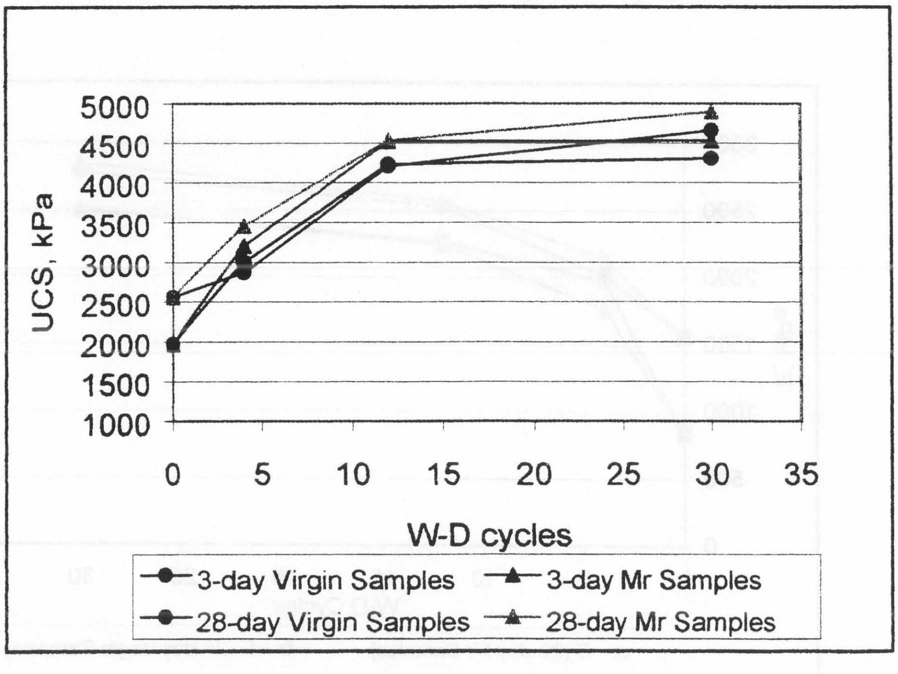


Figure 4-13 UCS Values of Virgin and Mr Samples of 3-Day and 28-Day Cured Samples Subjected to W-D Cycles

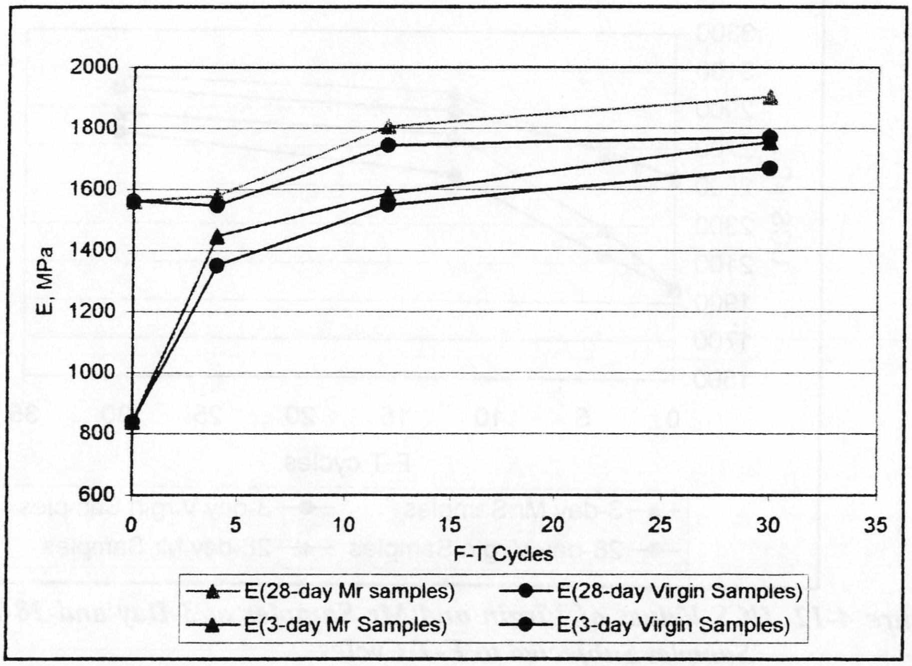


Figure 4-14 ***Modulus of Elasticity of Virgin and Mr Samples of 3-Day and 28-Day Cured Samples Subjected to F-T Cycles Determined by UCS Test***

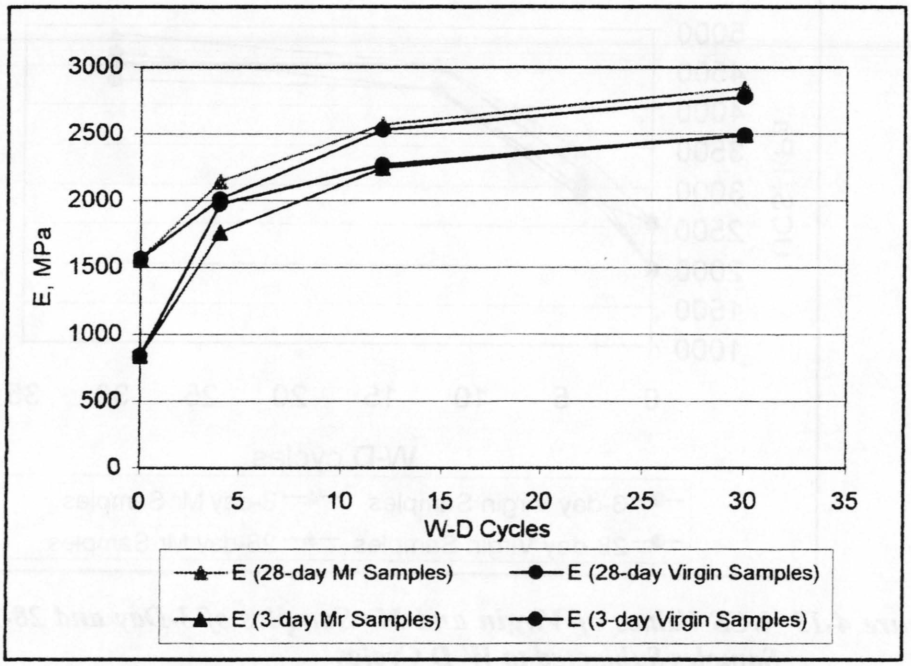


Figure 4-15 ***Modulus of Elasticity of Virgin and Mr Samples of 3-Day and 28-Day Cured Samples Subjected to W-D Cycles Determined by UCS Test***

5.1 General

The effect of F-T/W-D cycles on the resilient modulus of Meridian aggregate stabilized with CKD, FBA, and PC is presented and discussed in this chapter. In addition, resilient modulus results of F-T and W-D cycles of Richard Spur and Sawyer aggregates stabilized with CKD, CFA, and FBA are presented. The evaluation of F-T and W-D cycles on CKD- and FBA-stabilized Hanson aggregate are also presented and discussed herein. In addition, the relative effect of stabilizing agent is presented and discussed, as well as, the influence of aggregate type (mineralogy) in chemical stabilization.

5.2 Meridian Aggregate Stabilized with CKD, FBA, and PC

The Mr test was the only measurement used to identify the effect of F-T and W-D cycles on Meridian aggregate stabilized with CKD, FBA, and PC. Samples were compacted and molded according to the method described in Section 3.3. After compaction, samples were placed in a humidity room for 28 days before being subjected to F-T/W-D cycles, as shown in Figure 3-6. The number of F-T cycles was 0, 8, 16, and 30.

Tables 5-1 and 5-2 present the resilient modulus values of CKD-stabilized specimens cured for 28 days and subjected to F-T and W-D cycles, respectively. It is evident that the resilient modulus decreases as F-T and W-D cycles increases up to 16 cycles. For example, the resilient modulus (at S_3= 138 kPa and S_d = 69 kPa) of F-T specimens decreases approximately 40% and 75%, at 8 and 16 F-T cycles, respectively. At 30 F-T cycles, specimens degraded and the resilient modulus tests could not be performed. The damages caused by the freeze-thaw cycles could be contributed to the migration of moisture to the specimens that causes ice formation and disturbance of aggregate structure, specifically in the matrix of fine particles. Laboratory observation showed that the samples got wetter as the number of F-T cycles increased. Consequently, it is also obvious that the voids in the specimens could not accommodate the formation of ice lenses, due to the increase in moisture content after 16 cycles. Figure 5-1 illustrates the severe degradation of 15% CKD-stabilized aggregate base. From Table 5-1 and Figure 5-1, it is evident that the pressure caused by the formation of ice lenses is much higher than the bound between the fines and fly ash particles due to stabilization.

As for W-D specimens, the resilient modulus decreases from 1681 kPa (244 ksi) to 935 kPa (136 ksi), as W-D cycles increase from 0 to 30 cycles. Results are depicted in Table 5-2. It is likely that the cementitious reactions were not enhanced due to W-D cycles, and thus reduction in resilient modulus is observed. No tests such as Scanning Electron Microscopic and X-Ray diffraction tests were conducted to support his idea.

The effect of F-T and W-D cycles on the resilient modulus of FBA- and PC-stabilized aggregate specimens is presented in Tables 5-3 to 5-6. Results show that the resilient modulus for FBA-stabilized specimens decreased as F-T cycles increased up to 30 cycles. However, Mr values of PC-stabilized aggregate bases increased as F-T cycles increases up to 8 cycles, beyond which a reduction is shown. No major degradation of specimens has been seen. Thus, it is obvious that the bound due to stabilization is higher than the pressure exerted by the formation of ice lenses, and the voids in the specimens are not filled with enough water so that the expanding ice runs out of void space.

It is also interesting to note that the percentage decrease in resilient modulus of PC-stabilized specimens is lower than the FBA-stabilized specimens, but also lower than the CKD-stabilized aggregate based. For example: the resilient modulus of CKD-stabilized specimens subjected to 30 W-D cycles is approximately 65% lower than the corresponding Mr values of stabilized specimen with no such cycles, while Mr values of FBA-stabilized and PC-stabilized specimens (same stress levels and same number of cycles) are 40% and 20% lower, respectively, than the corresponding resilient modulus of specimens without any such cycles. As a result, it is evident that the stabilizing agent plays a major role in defining and evaluating the effect of durability of stabilized aggregate base.

5.3 Richard Spur Aggregate Stabilized with CKD, CFA, and FBA

The effect of F-T cycles and W-D cycles on the resilient modulus of Richard Spur aggregate stabilized with CKD, CFA, and FBA are presented in Tables 5-7 to 5-12.

Table 5-7 shows the variation of CKD-stabilized Richard Spur aggregate with different stress state and number of F-T cycles. It is obvious that a decrease in resilient modulus is observed as F-T cycles increase up to 30. The same trend was observed for W-D specimens, as given in Table 5-8. However, the effect of F-T cycle is more deleterious than the effect of W-D cycles. For instance, the resilient modulus of the stabilized specimens is approximately 88% lower than a specimen with zero F-T cycles, compared to approximately 35% reduction in resilient modulus of W-D specimens after 30 cycles. Consequently, the type of durability, either F-T or W-D cycles, could have different influence on the stabilized specimens.

Tables 5-9 and 5-10 present the resilient modulus of RS aggregate stabilized with CFA and subjected to F-T and W-D cycles, respectively. Form these results; it is observed that the resilient modulus decreases with increasing F-T and W-D cycles. The Mr values (at a deviatoric stress and confining pressure equal to 69 kPa (10psi)) decreased from 4893 MPa (710 ksi) to 794 MPa (115 ksi), due to 30 F-T cycles. Moreover, Richard Spur stabilized with 10% FBA exhibited a reduction in Mr values as the number of cycles increasing from zero to 30 cycles. Results are presented in Tables 5-11 and 5-12. The decrease in resilient modulus values of Richard Spur stabilized specimens is explained by the formation of ice lenses and the void space in the specimens for the F-T specimens, and by the cementitious reactions enhancement/retardation for W-D cycles, as discussed previously.

5.4 Sawyer Aggregate Stabilized with CKD, CFA, and FBA

The resilient modulus results of Sawyer specimens stabilized with CKD, CFA, and FBA, and subjected to different cycles of F-T and W-D cycles are given in Tables 5-13 to 5-18. Results show that the Mr at a given stress states decreases with the increase in the number of cycles. All specimens were subjected up to 30 cycles of F-T and W-D cycles, except for W-D specimens stabilized with FBA. FBA specimens subjected to 30 cycles were not tested due to degradation at the bottom of the specimens.

5.5 Hanson Aggregate stabilized with CKD and FBA

Hanson aggregates were stabilized with only CKD and FBA. Specimens were subjected up to 30 F-T cycles. Summary of the resilient modulus values are given in Tables 5-19 to 5-22. The resilient modulus of Hanson specimens had the same pattern as the other aggregate specimens. In other words, the resilient modulus showed a decrease as the number of F-T and W-D cycles increased from zero to 30 cycles. It is obvious from the tables, that the percentage reduction in resilient modulus due to F-T cycles is much higher that the corresponding Mr values of W-D specimens.

5.6 Conclusion

From the aforementioned results, it evident that the freeze-thaw damage is typically caused by the formation of ice lenses within the void space in the specimen. The severity of damages is a function of the amount of water in the specimens, or the amount of migrated water to the specimens. The void space in each specimen could play a major role, it either reduces the severity of ice formation to the specimen structure (high porosity), or it could increase it (low porosity).

As for W-D cycles, it can be concluded that the damages is a function of the retardation or acceleration of the cementitious or chemical reaction in the specimens, due to temperature and moisture content. No attempts were made to exactly examine the mechanism of cementitious reaction from a microscopic point of view.

In addition, the effect of F-T and W-D cycles can be influenced by the mineralogy of aggregate and its stabilizing agent. For example: Figure 5-2 compares the effect of aggregate mineralogy on the durability of CKD-stabilized aggregate base. It evident that CKD-stabilized Meridian aggregate has the lowest Mr values, followed by Hanson aggregate, and Sawyer. Richard Spur, on the other hand, has the highest Mr values. No attempts were made to quantify the effect of aggregate mineralogy on the durability of stabilized aggregate. Moreover, the stabilized agent could influence the durability of stabilized aggregate base. As an example; CKD stabilized Meridian aggregate has the lowest Mr values, followed by the CFA-, FBA-, and PC-stabilized aggregate specimens. Figure 5-3 illustrates qualitatively the effect of stabilizing agents on Meridian aggregate.

Table 5-1 Mr Values of CKD-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, and 16 Cycles of Freezing and Thawing.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	1681	244	1026	149	417	60
138	20	138	20	28	4	1784	259	1054	153	429	62
138	20	208	30	28	4	2210	321	1101	160	460	67
138	20	277	40	28	4	2277	330	1125	163	513	74
104	15	69	10	28	4	1652	240	922	134	364	53
104	15	138	20	28	4	1718	249	976	142	432	63
104	15	208	30	28	4	1914	278	992	144	518	75
104	15	277	40	28	4	2152	312	1029	149	564	82
69	10	69	10	28	4	1619	235	903	131	394	57
69	10	138	20	28	4	1692	246	945	137	446	65
69	10	208	30	28	4	1849	268	960	139	530	77
69	10	277	40	28	4	2119	308	1019	148	588	85
35	5	69	10	28	4	1609	234	875	127	402	58
35	5	138	20	28	4	1688	245	927	135	456	66
35	5	208	30	28	4	1835	266	933	135	536	78
35	5	277	40	28	4	2368	344	1003	146	596	86
0	0	69	10	28	4	1612	234	859	125	407	59
0	0	138	20	28	4	1673	243	893	130	457	66
0	0	208	30	28	4	1796	261	918	133	533	77
0	0	277	40	28	4	2093	304	997	145	597	87

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-2 Mr Values of CKD-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	1681	244	1299	189	1071	155	935	136
138	20	138	20	28	4	1784	259	1458	212	1183	172	935	136
138	20	208	30	28	4	2210	321	1550	225	1260	183	965	140
138	20	277	40	28	4	2277	330	1721	250	1405	204	1019	148
104	15	69	10	28	4	1652	240	1363	198	1039	151	660	96
104	15	138	20	28	4	1718	249	1364	198	1041	151	742	108
104	15	208	30	28	4	1914	278	1386	201	1081	157	835	121
104	15	277	40	28	4	2152	312	1489	216	1384	201	894	130
69	10	69	10	28	4	1619	235	1272	185	1008	146	624	91
69	10	138	20	28	4	1692	246	1307	190	1018	148	704	102
69	10	208	30	28	4	1849	268	1346	195	1033	150	796	115
69	10	277	40	28	4	2119	308	1403	204	1277	185	868	126
35	5	69	10	28	4	1609	234	1252	182	985	143	603	88
35	5	138	20	28	4	1688	245	1279	186	994	144	682	99
35	5	208	30	28	4	1835	266	1331	193	1006	146	773	112
35	5	277	40	28	4	2368	344	1375	200	1195	173	846	123
0	0	69	10	28	4	1612	234	1229	178	960	139	585	85
0	0	138	20	28	4	1673	243	1260	183	969	141	666	97
0	0	208	30	28	4	1796	261	1315	191	989	143	757	110
0	0	277	40	28	4	2093	304	1358	197	1151	167	838	122

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

θ = Bulk Stress

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-3 Mr Values of FBA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4500	653	3067	445	1552	225	791	115
138	20	138	20	28	4	4761	691	3473	504	1718	249	907	132
138	20	208	30	28	4	5039	731	4069	591	2050	298	996	145
138	20	277	40	28	4	6290	913	4320	627	2119	308	1077	156
104	15	69	10	28	4	4502	653	3205	465	1502	218	764	111
104	15	138	20	28	4	4502	653	3493	507	1650	240	843	122
104	15	208	30	28	4	4732	687	3057	444	1728	251	873	127
104	15	277	40	28	4	6289	913	4049	588	1987	288	1051	153
69	10	69	10	28	4	4488	651	3185	462	1582	230	771	112
69	10	138	20	28	4	4619	670	3471	504	1593	231	825	120
69	10	208	30	28	4	4700	682	3082	447	1750	254	868	126
69	10	277	40	28	4	6290	913	3644	529	1905	276	1030	150
35	5	69	10	28	4	4445	645	3181	462	1518	220	747	108
35	5	138	20	28	4	4589	666	2986	433	1581	229	795	115
35	5	208	30	28	4	4746	689	3507	509	1763	256	877	127
35	5	277	40	28	4	5620	816	3878	563	1994	289	1016	147
0	0	69	10	28	4	4438	644	3057	444	1443	209	735	107
0	0	138	20	28	4	4553	661	2940	427	1529	222	764	111
0	0	208	30	28	4	4726	686	3298	479	1616	234	824	120
0	0	277	40	28	4	5575	809	3688	535	1844	268	997	145

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-4 Mr Values of FBA-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4500	653	4538	659	4057	589	3493	507
138	20	138	20	28	4	4761	691	5462	793	4511	655	3647	529
138	20	208	30	28	4	5039	731	6157	894	5210	756	4118	598
138	20	277	40	28	4	6290	913	6658	966	5575	809	4870	707
104	15	69	10	28	4	4502	653	3948	573	3531	512	3166	460
104	15	138	20	28	4	4502	653	3951	573	3525	512	2714	394
104	15	208	30	28	4	4732	687	4193	609	3735	542	3001	436
104	15	277	40	28	4	6289	913	4297	624	3861	560	3330	483
69	10	69	10	28	4	4488	651	3581	520	3182	462	2876	417
69	10	138	20	28	4	4619	670	3639	528	3307	480	2532	367
69	10	208	30	28	4	4700	682	3942	572	3550	515	2846	413
69	10	277	40	28	4	6290	913	4174	606	3753	545	3240	470
35	5	69	10	28	4	4445	645	3456	502	3115	452	2820	409
35	5	138	20	28	4	4589	666	3518	511	3183	462	2428	352
35	5	208	30	28	4	4746	689	3824	555	3464	503	2775	403
35	5	277	40	28	4	5620	816	4100	595	3708	538	3202	465
0	0	69	10	28	4	4438	644	3371	489	3022	439	2742	398
0	0	138	20	28	4	4553	661	3427	497	3136	455	2389	347
0	0	208	30	28	4	4726	686	3768	547	3437	499	2753	399
0	0	277	40	28	4	5575	809	4110	597	3696	536	3192	463
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa													
σ_d = Deviator Stress													
σ_3 = Confining Pressure													
σ_s = Seating Pressure													
Mr = Resilient Modulus													

Table 5-5 Mr Values of PC-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	8822	1280	6637	963	4584	665	2865	416
138	20	138	20	28	4	9491	1377	8240	1196	4567	663	2854	414
138	20	208	30	28	4	11269	1636	8804	1278	5734	832	3584	520
138	20	277	40	28	4	12579	1826	10440	1515	5866	851	3666	532
104	15	69	10	28	4	8594	1247	7115	1033	4011	582	2507	364
104	15	138	20	28	4	8808	1278	7934	1152	4126	599	2578	374
104	15	208	30	28	4	9852	1430	8329	1209	4435	644	2772	402
104	15	277	40	28	4	11501	1669	9182	1333	4704	683	2940	427
69	10	69	10	28	4	8467	1229	7819	1135	3911	568	2444	355
69	10	138	20	28	4	8583	1246	7878	1143	4142	601	2589	376
69	10	208	30	28	4	9646	1400	7933	1151	4380	636	2738	397
69	10	277	40	28	4	11013	1598	8607	1249	4788	695	2993	434
35	5	69	10	28	4	8427	1223	7289	1058	4003	581	2502	363
35	5	138	20	28	4	8582	1246	7380	1071	4314	626	2696	391
35	5	208	30	28	4	9475	1375	7539	1094	4457	647	2786	404
35	5	277	40	28	4	10561	1533	8098	1175	4893	710	3058	444
0	0	69	10	28	4	8406	1220	7151	1038	4000	580	2500	363
0	0	138	20	28	4	8565	1243	7215	1047	4201	610	2626	381
0	0	208	30	28	4	9672	1404	7276	1056	4447	646	2780	403
0	0	277	40	28	4	10394	1509	7784	1130	4933	716	3083	448

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-6 Mr Values of PC-Stabilized Meridian Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	8822	1280	10581	1536	8048	1168	6530	948
138	20	138	20	28	4	9491	1377	11993	1741	8631	1253	7426	1078
138	20	208	30	28	4	11269	1636	12708	1844	9378	1361	8371	1215
138	20	277	40	28	4	12579	1826	13708	1990	10134	1471	8895	1291
104	15	69	10	28	4	8594	1247	10220	1483	7705	1118	6252	907
104	15	138	20	28	4	8808	1278	11296	1639	7788	1130	6294	914
104	15	208	30	28	4	9852	1430	12022	1745	7919	1149	6480	941
104	15	277	40	28	4	11501	1669	12813	1860	9024	1310	7567	1098
69	10	69	10	28	4	8467	1229	9731	1412	7949	1154	6671	968
69	10	138	20	28	4	8583	1246	10064	1461	7993	1160	6747	979
69	10	208	30	28	4	9646	1400	10066	1461	8088	1174	7255	1053
69	10	277	40	28	4	11013	1598	11428	1659	8511	1235	7637	1108
35	5	69	10	28	4	8427	1223	9528	1383	8046	1168	6746	979
35	5	138	20	28	4	8582	1246	9840	1428	8122	1179	6823	990
35	5	208	30	28	4	9475	1375	9911	1438	8557	1242	7223	1048
35	5	277	40	28	4	10561	1533	10918	1585	8888	1290	7518	1091
0	0	69	10	28	4	8406	1220	9334	1355	7009	1017	5937	862
0	0	138	20	28	4	8565	1243	9448	1371	7076	1027	6211	901
0	0	208	30	28	4	9672	1404	9946	1444	7745	1124	6582	955
0	0	277	40	28	4	10394	1509	10871	1578	8237	1195	7151	1038

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-7 Mr Values of CKD-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4387	637	2778	403	1843	267	463	67
138	20	138	20	28	4	4636	673	2759	400	1922	279	511	74
138	20	208	30	28	4	4995	725	3059	444	2168	315	544	79
138	20	277	40	28	4	5516	801	4914	713	2279	331	597	87
104	15	69	10	28	4	4318	627	2711	394	1768	257	417	60
104	15	138	20	28	4	4401	639	2783	404	1758	255	504	73
104	15	208	30	28	4	4755	690	3106	451	1975	287	603	88
104	15	277	40	28	4	5121	743	4992	725	1814	263	668	97
69	10	69	10	28	4	4290	623	2690	390	1710	248	448	65
69	10	138	20	28	4	4332	629	2823	410	1708	248	516	75
69	10	208	30	28	4	4671	678	3076	447	1920	279	612	89
69	10	277	40	28	4	4969	721	4779	694	1787	259	687	100
35	5	69	10	28	4	3907	567	2733	397	1668	242	477	69
35	5	138	20	28	4	4084	593	2862	415	1827	265	541	79
35	5	208	30	28	4	4104	596	3231	469	1675	243	628	91
35	5	277	40	28	4	4736	687	5070	736	1774	257	717	104
0	0	69	10	28	4	3968	576	2713	394	1625	236	476	69
0	0	138	20	28	4	4191	608	2699	392	1787	259	533	77
0	0	208	30	28	4	4198	609	2906	422	1653	240	635	92
0	0	277	40	28	4	5148	747	4516	655	1736	252	719	104

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-8 Mr Values of CKD-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4387	637	4062	590	3012	437	3322	482
138	20	138	20	28	4	4636	673	4248	617	3530	512	3315	481
138	20	208	30	28	4	4995	725	4625	671	5466	793	3547	515
138	20	277	40	28	4	5516	801	5003	726	5970	866	3556	516
104	15	69	10	28	4	4318	627	3877	563	3377	490	2632	382
104	15	138	20	28	4	4401	639	3992	579	3017	438	2787	404
104	15	208	30	28	4	4755	690	4357	632	3564	517	3043	442
104	15	277	40	28	4	5121	743	4792	695	2957	429	3300	479
69	10	69	10	28	4	4290	623	3929	570	3250	472	2557	371
69	10	138	20	28	4	4332	629	3931	571	2916	423	2762	401
69	10	208	30	28	4	4671	678	4194	609	3559	516	2993	434
69	10	277	40	28	4	4969	721	4650	675	2941	427	3284	477
35	5	69	10	28	4	3907	567	3648	529	3408	495	2517	365
35	5	138	20	28	4	4084	593	3656	531	3443	500	2765	401
35	5	208	30	28	4	4104	596	3704	538	2971	431	2965	430
35	5	277	40	28	4	4736	687	4210	611	2943	427	3257	473
0	0	69	10	28	4	3968	576	3527	512	3299	479	2453	356
0	0	138	20	28	4	4191	608	3732	542	3334	484	2739	397
0	0	208	30	28	4	4198	609	3763	546	2904	421	2943	427
0	0	277	40	28	4	5148	747	4737	688	2897	421	3239	470
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa													
σ_d = Deviator Stress													
σ_3 = Confining Pressure													
σ_s = Seating Pressure													
Mr = Resilient Modulus													

Table 5-9 Mr Values of CFA-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing.

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	5081	737	2907	422	2006	291	881	128
138	20	138	20	28	4	5529	803	2931	425	2336	339	922	134
138	20	208	30	28	4	6199	900	3147	457	2806	407	957	139
138	20	277	40	28	4	6579	955	3376	490	3539	514	1001	145
104	15	69	10	28	4	5013	728	2690	390	1998	290	773	112
104	15	138	20	28	4	5049	733	2853	414	2130	309	876	127
104	15	208	30	28	4	5140	746	3048	442	2312	336	948	138
104	15	277	40	28	4	5377	780	3324	482	3099	450	997	145
69	10	69	10	28	4	4893	710	2597	377	2000	290	794	115
69	10	138	20	28	4	5029	730	2758	400	2096	304	857	124
69	10	208	30	28	4	5046	732	2977	432	2265	329	944	137
69	10	277	40	28	4	5274	765	3199	464	2886	419	994	144
35	5	69	10	28	4	4994	725	2492	362	2001	290	777	113
35	5	138	20	28	4	5023	729	2761	401	2082	302	862	125
35	5	208	30	28	4	5050	733	2951	428	2258	328	935	136
35	5	277	40	28	4	5286	767	3156	458	2911	422	1004	146
0	0	69	10	28	4	4889	710	2471	359	2006	291	778	113
0	0	138	20	28	4	4974	722	2725	396	2087	303	878	127
0	0	208	30	28	4	5085	738	2912	423	2269	329	951	138
0	0	277	40	28	4	5147	747	3125	453	2887	419	1012	147

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-10 Mr Values of CFA-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	5081	737	4043	587	3576	519	3599	522
138	20	138	20	28	4	5529	803	4632	672	3855	560	3619	525
138	20	208	30	28	4	6199	900	5129	744	4246	616	3705	538
138	20	277	40	28	4	6579	955	6125	889	4391	637	3867	561
104	15	69	10	28	4	5013	728	4042	587	3470	504	3059	444
104	15	138	20	28	4	5049	733	4174	606	3700	537	3406	494
104	15	208	30	28	4	5140	746	4328	628	4193	609	3654	530
104	15	277	40	28	4	5377	780	5200	755	4473	649	3939	572
69	10	69	10	28	4	4893	710	4054	588	3471	504	3108	451
69	10	138	20	28	4	5029	730	4102	595	3767	547	3364	488
69	10	208	30	28	4	5046	732	4222	613	4237	615	3637	528
69	10	277	40	28	4	5274	765	4836	702	4522	656	3913	568
35	5	69	10	28	4	4994	725	4067	590	3418	496	3049	443
35	5	138	20	28	4	5023	729	4211	611	3779	548	3422	497
35	5	208	30	28	4	5050	733	4263	619	4179	607	3711	539
35	5	277	40	28	4	5286	767	4912	713	4475	649	3869	562
0	0	69	10	28	4	4889	710	4047	587	3389	492	2987	434
0	0	138	20	28	4	4974	722	4080	592	3819	554	3338	485
0	0	208	30	28	4	5085	738	4242	616	4067	590	3684	535
0	0	277	40	28	4	5147	747	5180	752	4469	649	3975	577
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa													
σ_d = Deviator Stress													
σ_3 = Confining Pressure													
σ_s = Seating Pressure													

Table 5-11 Mr Values of FBA-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	8691	1261	5181	752	2968	431	1704	247
138	20	138	20	28	4	8838	1283	5233	759	3262	473	1882	273
138	20	208	30	28	4	9062	1315	5361	778	3494	507	2084	302
138	20	277	40	28	4	11070	1607	5406	785	3711	539	2259	328
104	15	69	10	28	4	8798	1277	4645	674	2863	416	1534	223
104	15	138	20	28	4	8956	1300	4731	687	2908	422	1594	231
104	15	208	30	28	4	9404	1365	7406	1075	2920	424	1630	237
104	15	277	40	28	4	11675	1694	6523	947	3037	441	2396	348
69	10	69	10	28	4	8832	1282	5127	744	2963	430	1455	211
69	10	138	20	28	4	9120	1324	5424	787	2732	397	1393	202
69	10	208	30	28	4	9788	1421	6169	895	2827	410	1501	218
69	10	277	40	28	4	11987	1740	6602	958	2807	407	1559	226
35	5	69	10	28	4	8880	1289	5140	746	2852	414	1398	203
35	5	138	20	28	4	9142	1327	5502	799	2740	398	1359	197
35	5	208	30	28	4	9665	1403	5697	827	2725	396	1460	212
35	5	277	40	28	4	13030	1891	6657	966	2749	399	1531	222
0	0	69	10	28	4	8900	1292	5271	765	2745	398	1362	198
0	0	138	20	28	4	9205	1336	5520	801	2666	387	1318	191
0	0	208	30	28	4	9803	1423	6276	911	2673	388	1448	210
0	0	277	40	28	4	13296	1930	6731	977	2697	391	1524	221

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-12 Mr Values of FBA-Stabilized Richard Spur Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	8691	1261	7979	1158	5124	744	5461	793
138	20	138	20	28	4	8838	1283	8253	1198	5984	869	5675	824
138	20	208	30	28	4	9062	1315	8658	1257	7128	1035	6251	907
138	20	277	40	28	4	11070	1607	9318	1352	9058	1315	7617	1106
104	15	69	10	28	4	8798	1277	7414	1076	5174	751	5427	788
104	15	138	20	28	4	8956	1300	8253	1198	5761	836	5709	829
104	15	208	30	28	4	9404	1365	8708	1264	7290	1058	6247	907
104	15	277	40	28	4	11675	1694	9306	1351	8780	1274	7591	1102
69	10	69	10	28	4	8832	1282	7601	1103	5247	762	5485	796
69	10	138	20	28	4	9120	1324	8378	1216	5859	850	5685	825
69	10	208	30	28	4	9788	1421	8923	1295	7304	1060	6248	907
69	10	277	40	28	4	11987	1740	9321	1353	8540	1239	7203	1045
35	5	69	10	28	4	8880	1289	8101	1176	5408	785	5454	792
35	5	138	20	28	4	9142	1327	8196	1190	5971	867	5732	832
35	5	208	30	28	4	9665	1403	9101	1321	7279	1057	6189	898
35	5	277	40	28	4	13030	1891	9591	1392	8358	1213	7435	1079
0	0	69	10	28	4	8900	1292	8055	1169	5473	794	5400	784
0	0	138	20	28	4	9205	1336	8307	1206	6107	886	5564	808
0	0	208	30	28	4	9803	1423	8915	1294	8289	1203	5894	855
0	0	277	40	28	4	13296	1930	9644	1400	9448	1371	7283	1057

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-13 Mr Values of CKD-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3218	467	2166	314	1403	204	568	82
138	20	138	20	28	4	3646	529	2458	357	1480	215	592	86
138	20	208	30	28	4	4334	629	2641	383	1511	219	608	88
138	20	277	40	28	4	4820	700	2894	420	1617	235	677	98
104	15	69	10	28	4	3112	452	2175	316	1166	169	488	71
104	15	138	20	28	4	3447	500	2260	328	1293	188	512	74
104	15	208	30	28	4	3943	572	2563	372	1500	218	600	87
104	15	277	40	28	4	4546	660	2842	412	1668	242	677	98
69	10	69	10	28	4	3123	453	2177	316	1193	173	476	69
69	10	138	20	28	4	3408	495	2208	320	1314	191	526	76
69	10	208	30	28	4	3949	573	2522	366	1517	220	622	90
69	10	277	40	28	4	4306	625	2778	403	1701	247	680	99
35	5	69	10	28	4	3141	456	2184	317	1176	171	474	69
35	5	138	20	28	4	3338	484	2211	321	1295	188	518	75
35	5	208	30	28	4	4012	582	2527	367	1509	219	609	88
35	5	277	40	28	4	4134	600	2762	401	1701	247	708	103
0	0	69	10	28	4	3113	452	2211	321	1158	168	469	68
0	0	138	20	28	4	3377	490	2247	326	1280	186	512	74
0	0	208	30	28	4	3888	564	2515	365	1501	218	604	88
0	0	277	40	28	4	4063	590	2532	368	1699	247	679	99

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-14 Mr Values of CKD-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3218	467	4278	621	3295	478	2812	408
138	20	138	20	28	4	3646	529	4537	659	3612	524	2938	426
138	20	208	30	28	4	4334	629	5232	759	4178	606	3765	546
138	20	277	40	28	4	4820	700	6069	881	4184	607	4355	632
104	15	69	10	28	4	3112	452	4163	604	3346	486	3038	441
104	15	138	20	28	4	3447	500	4354	632	3552	516	2775	403
104	15	208	30	28	4	3943	572	4987	724	4550	660	3465	503
104	15	277	40	28	4	4546	660	5617	815	5002	726	2782	404
69	10	69	10	28	4	3123	453	4202	610	3430	498	2961	430
69	10	138	20	28	4	3408	495	4291	623	3606	523	2721	395
69	10	208	30	28	4	3949	573	4653	675	4953	719	3321	482
69	10	277	40	28	4	4306	625	5374	780	4972	722	2741	398
35	5	69	10	28	4	3141	456	4348	631	3427	497	2665	387
35	5	138	20	28	4	3338	484	4668	678	3598	522	3275	475
35	5	208	30	28	4	4012	582	4754	690	4851	704	2683	389
35	5	277	40	28	4	4134	600	5252	762	5012	727	2714	394
0	0	69	10	28	4	3113	452	4105	596	3590	521	2597	377
0	0	138	20	28	4	3377	490	4638	673	3597	522	3281	476
0	0	208	30	28	4	3888	564	4812	698	4767	692	2660	386
0	0	277	40	28	4	4063	590	5278	766	4798	696	2692	391

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-15 Mr Values of CFA-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	6411	930	3754	545	2743	398	1476	214
138	20	138	20	28	4	5567	808	3786	550	2989	434	1548	225
138	20	208	30	28	4	4075	591	3980	578	3161	459	1625	236
138	20	277	40	28	4	3778	548	4103	596	3298	479	1773	257
104	15	69	10	28	4	6253	908	3145	456	2472	359	1207	175
104	15	138	20	28	4	3903	566	3506	509	2789	405	1362	198
104	15	208	30	28	4	3789	550	3899	566	3088	448	1517	220
104	15	277	40	28	4	3803	552	4440	644	3329	483	1665	242
69	10	69	10	28	4	6651	965	3109	451	2556	371	1165	169
69	10	138	20	28	4	3899	566	3539	514	2773	402	1256	182
69	10	208	30	28	4	3797	551	3897	566	3083	447	1393	202
69	10	277	40	28	4	3768	547	4186	608	3335	484	1511	219
35	5	69	10	28	4	5259	763	3115	452	2549	370	896	130
35	5	138	20	28	4	3848	559	3387	492	2814	408	868	126
35	5	208	30	28	4	3670	533	3874	562	3088	448	1042	151
35	5	277	40	28	4	3748	544	4154	603	3326	483	1200	174
0	0	69	10	28	4	5054	734	2991	434	2549	370	661	96
0	0	138	20	28	4	3710	538	3532	513	2842	412	727	106
0	0	208	30	28	4	3720	540	3907	567	3116	452	784	114
0	0	277	40	28	4	3744	543	4237	615	3339	485	960	139

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-16 Mr Values of CFA-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	6411	930	3248	471	2596	377	2154	313
138	20	138	20	28	4	5567	808	3656	531	2898	421	2249	326
138	20	208	30	28	4	4075	591	4535	658	2908	422	2465	358
138	20	277	40	28	4	3778	548	5263	764	3006	436	2537	368
104	15	69	10	28	4	6253	908	3222	468	1901	276	1841	267
104	15	138	20	28	4	3903	566	2965	430	2164	314	1955	284
104	15	208	30	28	4	3789	550	3066	445	2582	375	2089	303
104	15	277	40	28	4	3803	552	3190	463	2936	426	2197	319
69	10	69	10	28	4	6651	965	2934	426	1766	256	1701	247
69	10	138	20	28	4	3899	566	2832	411	2094	304	1776	258
69	10	208	30	28	4	3797	551	2951	428	2483	360	1908	277
69	10	277	40	28	4	3768	547	3145	456	2886	419	2032	295
35	5	69	10	28	4	5259	763	2871	417	1683	244	1554	226
35	5	138	20	28	4	3848	559	2748	399	2043	296	1730	251
35	5	208	30	28	4	3670	533	2924	424	2433	353	1853	269
35	5	277	40	28	4	3748	544	3111	452	2808	407	1931	280
0	0	69	10	28	4	5054	734	2742	398	1537	223	1395	203
0	0	138	20	28	4	3710	538	2712	394	1895	275	1526	222
0	0	208	30	28	4	3720	540	2902	421	2305	335	1701	247
0	0	277	40	28	4	3744	543	3097	449	2709	393	1853	269

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-17 Mr Values of FBA-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4146	602	4825	700	1469	213	722	105
138	20	138	20	28	4	4617	670	4312	626	1603	233	816	118
138	20	208	30	28	4	4988	724	3563	517	1583	230	769	112
138	20	277	40	28	4	5222	758	3162	459	1462	212	703	102
104	15	69	10	28	4	4119	598	3011	437	1313	191	535	78
104	15	138	20	28	4	4306	625	2803	407	1310	190	554	80
104	15	208	30	28	4	4588	666	2952	429	1415	205	592	86
104	15	277	40	28	4	5002	726	3078	447	1482	215	640	93
69	10	69	10	28	4	4113	597	2822	410	1270	184	467	68
69	10	138	20	28	4	4254	617	2715	394	1308	190	524	76
69	10	208	30	28	4	4505	654	2922	424	1402	203	580	84
69	10	277	40	28	4	5344	776	3106	451	1507	219	630	91
35	5	69	10	28	4	4128	599	2880	418	1288	187	367	53
35	5	138	20	28	4	4236	615	2689	390	1305	189	434	63
35	5	208	30	28	4	4541	659	2899	421	1389	202	497	72
35	5	277	40	28	4	5241	761	3113	452	1506	219	551	80
0	0	69	10	28	4	4133	600	2812	408	1306	190	240	35
0	0	138	20	28	4	4204	610	2694	391	1310	190	327	48
0	0	208	30	28	4	4492	652	2845	413	1393	202	403	59
0	0	277	40	28	4	5358	778	3126	454	1524	221	467	68

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-18 Mr Values of FBA-Stabilized Sawyer Aggregate Cured for 28 Days and Subjected to 0, 8, and 16 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	4146	602	3091	449	1002	145
138	20	138	20	28	4	4617	670	3358	487	1095	159
138	20	208	30	28	4	4988	724	3745	544	1278	185
138	20	277	40	28	4	5222	758	4055	589	1317	191
104	15	69	10	28	4	4119	598	2953	429	713	104
104	15	138	20	28	4	4306	625	2765	401	781	113
104	15	208	30	28	4	4588	666	2823	410	905	131
104	15	277	40	28	4	5002	726	2836	412	968	140
69	10	69	10	28	4	4113	597	2459	357	665	96
69	10	138	20	28	4	4254	617	2441	354	734	107
69	10	208	30	28	4	4505	654	2551	370	864	125
69	10	277	40	28	4	5344	776	2620	380	956	139
35	5	69	10	28	4	4128	599	2242	325	652	95
35	5	138	20	28	4	4236	615	2145	311	718	104
35	5	208	30	28	4	4541	659	2193	318	841	122
35	5	277	40	28	4	5241	761	2252	327	944	137
0	0	69	10	28	4	4133	600	1890	274	624	91
0	0	138	20	28	4	4204	610	1892	275	708	103
0	0	208	30	28	4	4492	652	1989	289	837	121
0	0	277	40	28	4	5358	778	2091	304	947	138

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-19 Mr Values of CKD-Stabilized Hanson Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		16 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2585	375	1260	183	625	91	228	33
138	20	138	20	28	4	2767	402	1321	192	677	98	265	38
138	20	208	30	28	4	2843	413	1493	217	712	103	285	41
138	20	277	40	28	4	3221	467	1562	227	756	110	312	45
104	15	69	10	28	4	2601	378	1145	166	528	77	217	32
104	15	138	20	28	4	2603	378	1171	170	571	83	242	35
104	15	208	30	28	4	2707	393	1229	178	653	95	284	41
104	15	277	40	28	4	3140	456	1336	194	740	107	317	46
69	10	69	10	28	4	2559	371	1097	159	474	69	201	29
69	10	138	20	28	4	2578	374	1133	164	528	77	237	34
69	10	208	30	28	4	2640	383	1205	175	613	89	277	40
69	10	277	40	28	4	2972	431	1254	182	701	102	315	46
35	5	69	10	28	4	2586	375	1072	156	435	63	207	30
35	5	138	20	28	4	2596	377	1103	160	497	72	234	34
35	5	208	30	28	4	2754	400	1184	172	583	85	275	40
35	5	277	40	28	4	3035	440	1192	173	669	97	314	46
0	0	69	10	28	4	2557	371	1042	151	395	57	195	28
0	0	138	20	28	4	2597	377	1087	158	458	66	231	33
0	0	208	30	28	4	2718	394	1166	169	549	80	272	39
0	0	277	40	28	4	2996	435	1178	171	643	93	315	46

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-20 Mr Values of CKD-Stabilized Hanson Aggregate Cured for 28 Days and Subjected to 0, 8, 16, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		16 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	2585	375	2179	316	1618	235	1519	220
138	20	138	20	28	4	2767	402	2328	338	1798	261	1672	243
138	20	208	30	28	4	2843	413	2524	366	2102	305	1735	252
138	20	277	40	28	4	3221	467	2752	399	2302	334	1823	265
104	15	69	10	28	4	2601	378	2124	308	1595	231	1468	213
104	15	138	20	28	4	2603	378	2154	313	1638	238	1484	215
104	15	208	30	28	4	2707	393	2155	313	1749	254	1554	225
104	15	277	40	28	4	3140	456	2425	352	2273	330	1574	228
69	10	69	10	28	4	2559	371	2032	295	1565	227	1421	206
69	10	138	20	28	4	2578	374	2049	297	1603	233	1457	212
69	10	208	30	28	4	2640	383	2074	301	1666	242	1478	215
69	10	277	40	28	4	2972	431	2194	318	2201	319	1533	223
35	5	69	10	28	4	2586	375	2014	292	1558	226	1392	202
35	5	138	20	28	4	2596	377	2029	294	1574	228	1435	208
35	5	208	30	28	4	2754	400	2075	301	1656	240	1438	209
35	5	277	40	28	4	3035	440	2193	318	2111	306	1506	219
0	0	69	10	28	4	2557	371	1947	283	1543	224	1373	199
0	0	138	20	28	4	2597	377	1958	284	1550	225	1411	205
0	0	208	30	28	4	2718	394	2020	293	1634	237	1421	206
0	0	277	40	28	4	2996	435	2195	319	2068	300	1458	212
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa													
σ_d = Deviator Stress													
σ_3 = Confining Pressure													
σ_s = Seating Pressure													
Mr = Resilient Modulus													

Table 5-21 Mr Values of FBA-Stabilized Hanson Aggregate Cured for 28 Days and Subjected to 0, 8, and 30 Cycles of Freezing and Thawing

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 F-T cycle		8 F-T cycles		30 F-T cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3440	499	2464	358	1726	251
138	20	138	20	28	4	3786	549	2513	365	1850	269
138	20	208	30	28	4	4129	599	2929	425	2141	311
138	20	277	40	28	4	4464	648	3351	486	2244	326
104	15	69	10	28	4	3392	492	2317	336	1427	207
104	15	138	20	28	4	3434	498	2446	355	1620	235
104	15	208	30	28	4	3525	512	2756	400	1815	263
104	15	277	40	28	4	3821	555	3316	481	1999	290
69	10	69	10	28	4	3405	494	1962	285	1121	163
69	10	138	20	28	4	3426	497	2398	348	1328	193
69	10	208	30	28	4	3455	502	2827	410	1526	222
69	10	277	40	28	4	3821	555	3255	472	1720	250
35	5	69	10	28	4	3362	488	1685	245	967	140
35	5	138	20	28	4	3392	492	1749	254	1017	148
35	5	208	30	28	4	3476	504	2188	318	1229	178
35	5	277	40	28	4	3751	544	2596	377	1420	206
0	0	69	10	28	4	3392	492	1595	231	744	108
0	0	138	20	28	4	3427	497	1693	246	837	121
0	0	208	30	28	4	3503	508	1962	285	911	132
0	0	277	40	28	4	3749	544	2495	362	1125	163

1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

σ_d = Deviator Stress

σ_3 = Confining Pressure

σ_s = Seating Pressure

Mr = Resilient Modulus

Table 5-22 Mr Values of FBA-Stabilized Hanson Aggregate Cured for 28 Days and Subjected to 0, 8, and 30 Cycles of Wetting and Drying

σ_3 (kPa)	σ_3 (psi)	σ_d (kPa)	σ_d (psi)	σ_s (kPa)	σ_s (psi)	0 W-D cycle		8 W-D cycles		30 W-D cycles	
						Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)	Mr (MPa)	Mr (ksi)
138	20	69	10	28	4	3440	499	2902	421	2504	363
138	20	138	20	28	4	3786	549	2924	424	2624	381
138	20	208	30	28	4	4129	599	3060	444	2418	351
138	20	277	40	28	4	4464	648	3193	463	2517	365
104	15	69	10	28	4	3392	492	2496	362	1814	263
104	15	138	20	28	4	3434	498	2595	377	2009	292
104	15	208	30	28	4	3525	512	2917	423	2227	323
104	15	277	40	28	4	3821	555	3180	462	2340	340
69	10	69	10	28	4	3405	494	2364	343	1724	250
69	10	138	20	28	4	3426	497	2549	370	1883	273
69	10	208	30	28	4	3455	502	2881	418	2090	303
69	10	277	40	28	4	3821	555	3160	459	2302	334
35	5	69	10	28	4	3362	488	2382	346	1694	246
35	5	138	20	28	4	3392	492	2530	367	1846	268
35	5	208	30	28	4	3476	504	2885	419	2043	297
35	5	277	40	28	4	3751	544	3205	465	2250	326
0	0	69	10	28	4	3392	492	2437	354	1106	161
0	0	138	20	28	4	3427	497	2658	386	1263	183
0	0	208	30	28	4	3503	508	2945	427	1458	212
0	0	277	40	28	4	3749	544	3278	476	1632	237
1 psi = 6.89 kPa; 1 ksi = 6.89 MPa											
σ_d = Deviator Stress											
σ_3 = Confining Pressure											
σ_s = Seating Pressure											
Mr = Resilient Modulus											

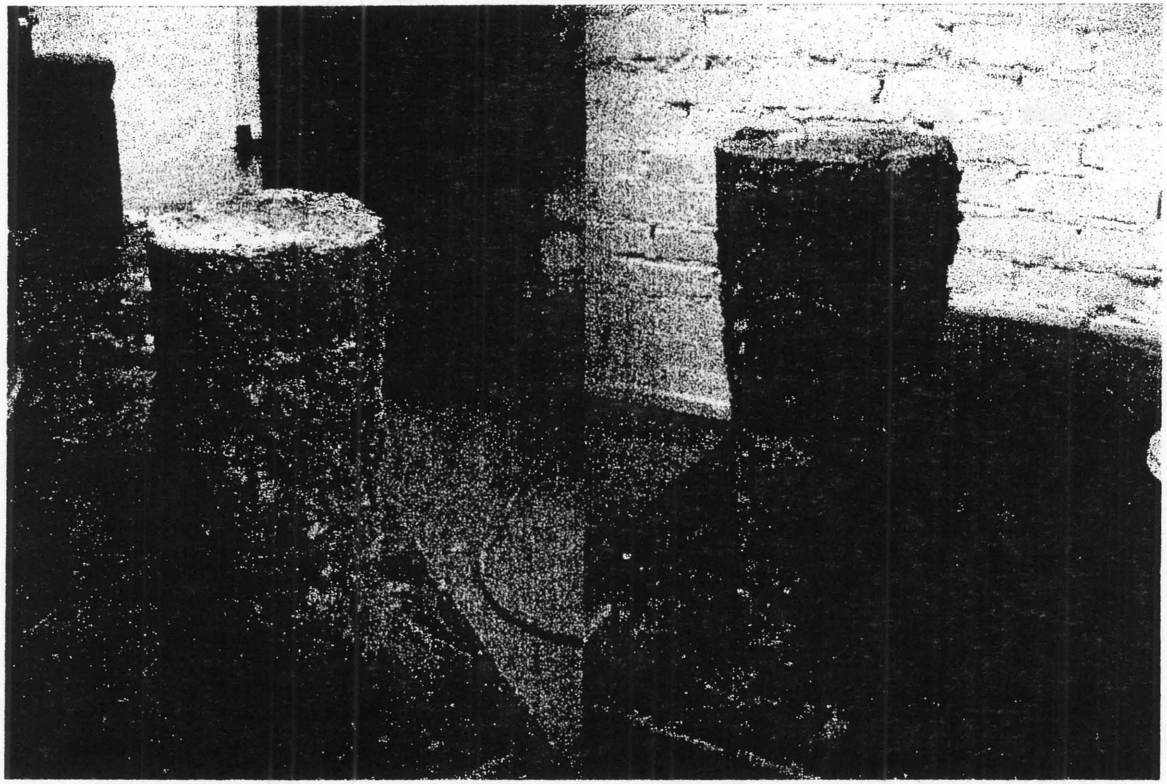


***Figure 5-1** Meridian Aggregate Samples (Duplicate) Stabilized with 15% CKD and Subjected to 30 F-T Cycles; Samples could not be Tested Due to Excessive Degradation*

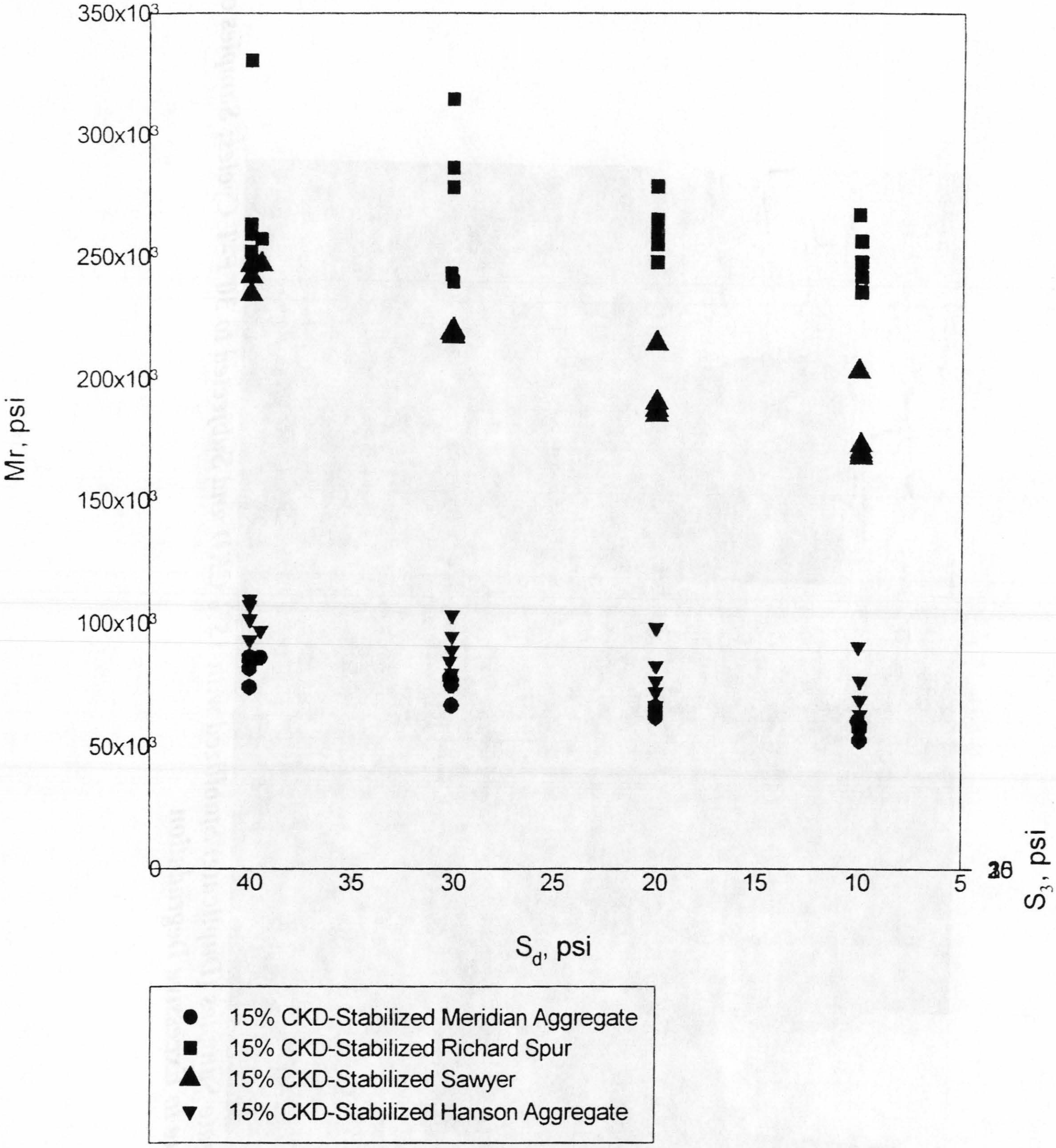


Figure 5-2 Relative Effect of Aggregate Type on the Durability of Stabilized Specimens

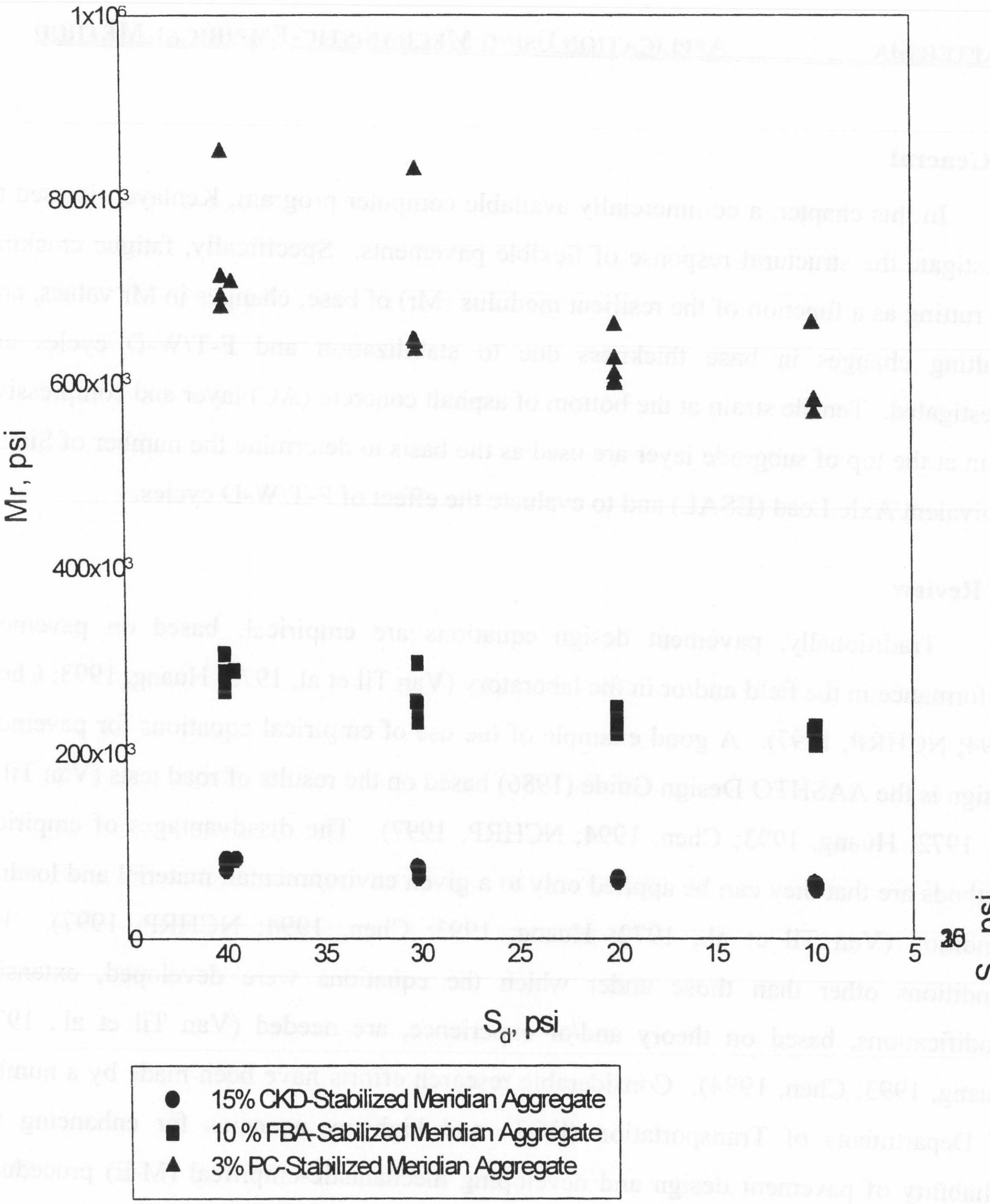


Figure 5-3 Relative Effect of Stabilizing Agent on the Durability of Stabilized Meridian Aggregate Specimens

6.1 General

In this chapter, a commercially available computer program, Kenlayer, is used to investigate the structural response of flexible pavements. Specifically, fatigue cracking and rutting as a function of the resilient modulus (Mr) of base, changes in Mr values, and resulting changes in base thickness due to stabilization and F-T/W-D cycles are investigated. Tensile strain at the bottom of asphalt concrete (AC) layer and compressive strain at the top of subgrade layer are used as the basis to determine the number of Single Equivalent Axle Load (ESAL) and to evaluate the effect of F-T/W-D cycles.

6.2 Review

Traditionally, pavement design equations are empirical, based on pavement performance in the field and/or in the laboratory (Van Til et al, 1972; Huang, 1993; Chen, 1994; NCHRP, 1997). A good example of the use of empirical equations for pavement design is the AASHTO Design Guide (1986) based on the results of road tests (Van Til et al., 1972; Huang, 1993; Chen, 1994; NCHRP, 1997). The disadvantages of empirical methods are that they can be applied only to a given environmental, material and loading condition (Van Til et al., 1972; Huang, 1993; Chen, 1994; NCHRP, 1997). For conditions other than those under which the equations were developed, extensive modifications, based on theory and/or experience, are needed (Van Til et al., 1972; Huang, 1993; Chen, 1994). Considerable research efforts have been made by a number of Departments of Transportation (DOT) and highway agencies for enhancing the reliability of pavement design and developing mechanistic-empirical (M-E) procedures for the thickness design of new flexible and rigid pavements (Huang, 1993; NCHRP, 1992). The M-E methods are based on the mechanics of materials that relate wheel-load to pavement response, such as stress or strain (Huang, 1993; Chen, 1994). The response values are used to predict pavement distress based on laboratory tests and/or field performance data (Huang, 1993). Pavement performance-related field data is particularly useful because theory alone may not be sufficient to design pavement with superior performance during its service life. The advantages of the M-E method are the improvement of reliability in design, the ability to predict the type of distress, and the feasibility to extrapolate from limited field and/or laboratory data (Huang, 1993). According to NCHRP (1992), the M-E pavement design is now "a reality." Permanent deformation or rutting is a common distress in pavement. As reported by Huang (1993), the first use of vertical compressive strain at the top of subgrade as a criterion for rutting was suggested by Kerkhoven and Dormon (1953). The use of this criterion is based on the fact that plastic strains are proportional to elastic strains in paving materials (Huang, 1993). Thus, by limiting the elastic strains in the subgrade, the elastic strains of other layers above the subgrade and the permanent deformation of the pavement surface can be controlled (Huang, 1993). In recent years, however, it has been demonstrated that rutting can be induced by many other factors and mechanisms (Roberts et al., 1996). Additionally, it was reported in literature that the horizontal tensile strain at the bottom of an asphalt layer has been used as a criterion for fatigue cracking. The fatigue cracking and rutting in pavement under a wheel load are illustrated in Figure 6-1. These two criteria have been adopted and used by several agencies, such as Shell Petroleum International (Claussen et al., 1977) and Asphalt Institute (AI, 1991) in developing mechanistic-empirical methods for pavement design (Huang, 1993; Chen, 1994; NCHRP, 1992).

6.3 Distress Models

Distress is an important factor in the mechanistic-empirical (M-E) methods. Design of pavements based on such methods requires development of criteria addressing specific distresses. Also, the evaluation of pavement distress is an important part of pavement management so that an effective strategy for maintenance and rehabilitation can be developed (Huang, 1993). In this study, the aforementioned distresses, namely, fatigue cracking, and rutting, are used as the criteria for pavement performance. The effect of base modulus on pavement performance is examined via the software, Kenlayer. An excellent review on identifying different types of pavement distress is given by Smith et al. (1979).

6.3.1 Fatigue Cracking

Alligator or fatigue cracking is caused by the fatigue failure of an asphalt layer under repeated traffic load (Huang, 1993). Two types of fatigue cracking models have been reported in the literature: (i) strain/modulus-based models, and (ii) strain-based models (Huang, 1998; Chen, 1994). Mathematically, they can be expressed by the following equations, respectively:

$$\mathbf{N_f = f1 \times (\varepsilon_t)^{-f2} \times (E_{ac})^{-f3}} \qquad \textit{(6- 1)}$$

$$\mathbf{N_f = f1 \times (\varepsilon_t)^{-f2}} \qquad \textit{(6- 2)}$$

where, N_f is the allowable number of load repetitions to prevent fatigue cracking, ε_t is the tensile strain at the bottom of the AC layer, and E_{ac} is the modulus of elasticity of asphalt concrete (AC) layer in psi. f2 and f3 are constants determined from laboratory tests. The other constant (f1) is also based on laboratory data, but modified to correlate with field observations (Chen, 1994, Huang 1998). The fatigue cracking criteria used by various agencies are given in Table 6-1. The fatigue cracking given by Equation 6-1 was employed by the Asphalt Institute (AI) and Shell based on the concept developed in the NCHRP-1-10B report (Chen, 1994). However, the Illinois DOT, the University of Illinois (Thompson, 1987), the Transportation and Road Research Laboratory (TRRL) in the U.K. and other agencies employed the strain-based model given in Equation 6-2, for simplicity in evaluating rutting (Chen, 1994).

6.3.2 Permanent Deformation or Rutting

Rutting is caused by the consolidation of the paving materials due to traffic loads. In the Asphalt Institute and Shell methods, the number of load repetitions, N_d, that a pavement can withstand before having any rutting problems is related to the compressive strain at the top of subgrade and given by Equation 6-3 (Chen, 1994; Huang, 1993; NCHRP, 1992):

$$\mathbf{N_d = f4 \times (\varepsilon_c)^{-f5}} \qquad \textit{(6- 3)}$$

where N_d is the maximum number of load repetitions to limit permanent deformation, ε_c is the compressive strain at the top of the subgrade layer, and f4 and f5 are constant given in Table 6-2. The values of N_d acceptable to the AI are related to rut depth not greater than 12.7 mm (0.5 in). The Shell method estimates permanent deformation according to Equation 6-4 (Huang, 1993)

$$\textbf{Rut depth} = C_m\, h_l\, (\sigma_{av}/S_{max}) \qquad (6\text{-}4)$$

in which C_m is a correction factor for dynamic effect with values ranging from one to two depending on the type of mix, h_l is the thickness of the asphalt layer, σ_{av} is the average vertical stress in the asphalt layer, and S_{max} is the stiffness of the mix. Chen (1994) reported that the variation of predicted service life based on this rutting model (Equation 6-3) is smaller than that predicted by the fatigue cracking model (Equation 6-1). In the present study, both models adopted by the Asphalt Institute are used to determine the allowable load repetition (i.e., equivalent single axle load) that a pavement can withstand before it exhibits fatigue cracking or rutting.

6.4 Design Application

6.4.1 Kenlayer

The software Kenlayer, developed by Huang (1993), was used to evaluate the effect of varying base modulus on the response of flexible pavements. This software is based on the Burmister's multilayer elastic (MLE) theory (Fanous et al., 1999; and Chen, 1994). Kenlayer assumes a circular loading area with a uniform distribution of pressure applied on the pavement surface. All layers are assumed to have fully frictional interfaces and all materials are assumed to be linear elastic (Fanous et al., 1999; and Chen, 1994). The input is created using the LAYERINP program. The features of the program and the input parameters are given by Huang (1993). The output is a TXT file called "LAYER.TXT." It contains the output parameters such as stresses and strains, and the input parameters.

6.4.2 Flexible Pavement Design Examples

The generic pavement analyzed here is composed of a three-layer system including an asphalt layer and a granular base on the top of the subgrade, as shown in Figure 6.2. Three different asphalt layer thickness was used, namely, 152.4 mm (6 in), 228.6 mm (9 in), and 304.8 mm (12 in), while the modulus of the AC layer was constant and equal to 3105 MPa (450 ksi). The subgrade is assumed to be semi-infinite. Four different subgrade moduli were used. In addition, the main variables considered are the thickness of the base layer (H_b) and its modulus (M_r).

6.4.3 Discussion of Results

The computed ESAL values are listed in Tables 6-3 to 6-5. It is evident that an increase in the resilient modulus of aggregate bases increases ESAL, therefore, stabilization of aggregate base with different additive agents increases the number of ESAL. For example, ESAL increase more than 20 times as resilient modulus increases from 137,800 kPa (20,000 psi) to 6,890 MPa (1,000 ksi), due to stabilization. In addition, the ESAL value could be affect by the number of F-T/W-D cycles. For example, ESAL decrease if F-T/W-D cycles cause a decrease in resilient modulus of aggregate base. On the other hand, ESAL increase due to positive effect of F-T/W-D on resilient modulus of stabilized aggregate base.

6.5 Direct Application

In mechanistic-empirical methods, determining the resilient modulus in function of stress state is important and plays an important role in implementing pavement design and evaluation of pavement performance. More than 14 regression equations of resilient modulus have been reported in the literature (NCHRP, 2000). In this study, the stress-dependent models including deviatoric stress and confining pressure (see Equation 6-5) of stabilized and raw materials were developed based on the results of resilient modulus presented in Chapters 4 and 5.

$$M_r = k_1 \times S_d^{\,k_2} \times S_3^{\,k_3} \qquad \textbf{\textit{(6-5)}}$$

Where,

Mr: Resilient Modulus

S_d: Deviatoric stress

S_3: Absolute confining pressure

k_1, k_2, k_3: Model parameters

Summary of model parameters is given in Tables 6-6 to 6-10, from which one can determine the resilient modulus of the stabilized aggregate base with different stabilizing agents. Tables 6-10 to 6-12 present the number of ESAL by using a mechanistic-empirical method. Those Tables were developed for a 3-layer pavement having a constant AC modulus, and different combination of AC thickness, base thickness and modulus, and different subgrade modulus. The significant of those Tables will be demonstrated through an example.

Example :

Given the following information for a 3-layer pavement structure:

1) Modulus of asphalt layer (E_{ac}) is approximately 450 ksi
2) AC layer thickness (H_{ac}) is approximately 6 inches
3) Aggregate base consists of Meridian aggregate stabilized with FBA, and a thickness of 8 inches.
4) Subgrade resilient modulus is approximately 10,000 psi.

Question I: Determine ESAL, if the pavement is subjected to 0 F-T cycles? (P.S.: The deviatoric stress and confining pressure in the subgrade are expected to be 20 psi, and 10 psi, respectively.

Procedure & Answer to Question I:

Table 6-6 illustrates the resilient modulus of Meridian aggregate base stabilized with FBA. Given 0 F-T cycles, hence, the model parameters to determine the resilient modulus are:

a. $k_1 = 337443$
b. $k_2 = 0.175$
c. $k_3 = 0.067$
d. given $S_d = 20$ psi & $S_3 = 10$ psi (24.65 psi absolute), thus

$$M_r = 337443 \times 20^{0.175} \times 24.65^{0.067} \cong 706533 \text{psi}$$

Given, $H_{ac} = 6$ inches, thus Table 6-10 will be used to determine the number of ESAL.

a. Given $H_b = 8$ inches, and resilient modulus of subgrade equals 10, 000 psi, thus , the model parameters for ESAL are:
   i. $m_1 = 211{,}000$
   ii. $m_2 = 1.29$

iii. m_3 = 7.68E-05

iv. m_4 = -9.93E-14

v. Thus,

$$ESAL = 211000 + 1.29 \times 706533 + (7.68E-05) \times 706533^2 + (-9.93E-14) \times 706533^3$$
$$= 39495156 \cong 4E+07$$

Question II: Determine ESAL, if the pavement consists of Richard Spur aggregate base stabilized with CKD and subjected to 8 W-D cycles. The modulus of subgrade is 5,000 psi. in addition, the modulus of AC layer and thickness are 450 ksi, and 12 inches, respectively. The same stress states, given in the previous question, are expected to be the same.

Procedure & Answer to Question II

Table 6.7 illustrates the resilient modulus of Richard Spur aggregate base stabilized with CKD. Given 8 W-D cycles, hence, the model parameters to determine the resilient modulus are:

e. k_1 = 234,639

f. k_2 = 0.130

g. k_3 = 0.168

h. given S_d = 20 psi & S_3 = 10 psi (24.65 psi absolute), thus

$$M_r = 234639 \times 20^{0.130} \times 24.65^{0.168} \cong 593323 \text{ psi}$$

Given, Hac = 12 inches, thus Table 6.12 will be used to determine the number of ESAL.

b. Given Hb = 8 inches, and resilient modulus of subgrade equals 5, 000 psi, thus , the model parameters for ESAL are:

i. m_1 = 3, 990, 000

ii. m_2 = 56.40

iii. m_3 = 5.72E-04

iv. m_4 = -8.81E-11

v. Thus,

$$ESAL = 3{,}990{,}000 + 56.40 \times 593323 + (5.72E-04) \times 593323^2 + (-8.81E-11) \times 593323^3$$
$$= 257217166 \cong 2.60E+08$$

Alternate Ways

Tables 4.1-4.11 and 5.1-5.22 can be used to determine the resilient modulus of different aggregate types instead of using the regression models presented in Tables 6-6 to 6-12. After the determination of resilient modulus, Tables 6-3 to 6-5 can be used for evaluating the number of ESAL.

Solving question I by using this method.

From Table 5-3, the resilient modulus of Meridian aggregate stabilized with FBA at the given stress state is approximately 670,000 psi. Given H_{ac} of 6 inches, Table 6.3 will be used to determine the number of ESAL. Since, M_r = 670, 000 is not in Table 6.3, linear interpolation could be used. Given H_b = 8 inches and M_r subgrade equals 10, 000 psi, thus,

ESAL (@ M_r base = 400 ksi) is equal to 1.3E+07, and

ESAL (@ M_r base = 750 ksi) is equal to 4.5E+07

Using linear interpolation, ESAL will be equal to 3.8E+07, compared to 4.0E+07 from the previous method.

Table 6-1 Fatigue Cracking Criteria Used by Various Agencies (After Chen, 1994)

Agency	f1	f2	f3	E_{ac}
AI (AI, 1982)	0.0796	3.291	0.854	Unit in psi
Shell (Shell, 1978)	6.387×10^{-8}	5.0	1.8	Unit in ksi
Illinois (Thompson, 1987)	5×10^{-6}	3.0		

Table 6-2 Rutting Criteria Used by Various Agencies (After Chen, 1994)

Agency	f4	f5	Rut depth, (in)
AI (AI, 1982)	1.365×10^{-9}	4.477	0.5
Shell (Shell, 1978)			
50% R	6.15×10^{-7}	4.0	
85% R	1.94×10^{-7}	4.0	
95% R	1.05×10^{-7}	4.0	

Table 6-3 ESAL Obtained from the Computer Program Kenlayer (H_{ac} = 6 inches)

Subgrade Modulus (1ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, (psi)				
20000	1220	3580	6450	11600
250000	20700	29400	904000	2480000
400000	46900	796000	2570000	7290000
750000	135000	2760000	9500000	28300000
1000000	216000	4820000	17200000	52500000
2000000	597670	17967000	71294000	230900000

Subgrade Modulus (5ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, (psi)				
20000	18700	62300	112000	199000
250000	168000	2060000	5880000	15100000
400000	369000	5380000	16200000	43400000
750000	1030000	18000000	59500000	171000000
1000000	1660000	33000000	110000000	326000000
2000000	4699900	124370000	477370000	1596200000

Subgrade Modulus (10ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, (psi)				
20000	84759	313942	579117	717931
250000	452202	5247820	14628841	37096186
400000	933819	12982486	38530002	102123742
750000	2573025	44500000	142480000	402350000
1000000	4064502	78114000	260310000	760210000
2000000	11793000	309220000	1155100000	3725300000

Subgrade Modulus (20ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, (psi)				
20000	543420	830790	830790	830790
250000	1375400	14844000	40834000	98816000
400000	2650600	34589000	101130000	265560000
750000	6885100	113950000	360940000	1010400000
1000000	10723000	199020000	656140000	1897300000
2000000	30831000	794430000	2931900000	9270300000

Table 6-4 ESAL Obtained from the Computer Program Kenlayer (H_{ac} = 9 inches)

Subgrade Modulus (1 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	26584	52586	78037	117540
250000	209470	1782300	4568500	10747000
400000	432390	4468200	11973000	28906000
750000	1196700	14499000	40311000	99429000
1000000	1884800	24041000	67953000	169500000
2000000	5154500	75846000	227140000	590010000

Subgrade Modulus (5 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	324000	803200	1255300	1936300
250000	1570700	11711000	28176000	63219000
400000	3048800	27431000	70086000	165340000
750000	7910000	86353000	236940000	595610000
1000000	12220000	144350000	410260000	1065600000
2000000	32953000	486510000	1542400000	4423500000

Subgrade Modulus (10 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	1302000	3773200	4010600	4149500
250000	4062200	29521000	70042000	154730000
400000	7573500	66281000	166910000	387220000
750000	18968000	203030000	549040000	1355100000
1000000	29033000	338250000	946920000	2412200000
2000000	77942000	1148600000	3568300000	10007000000

Subgrade Modulus (20 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	5023100	5023100	5023100	5023100
250000	11667000	82706000	194300000	267930000
400000	20424000	173450000	433040000	996920000
750000	48201000	506610000	1363300000	3340500000
1000000	72508000	837340000	2335200000	5899100000
2000000	191320000	2859800000	8827600000	24343000000

Table 6-5 ESAL Obtained from the Computer Program Kenlayer (H_{ac} = 12 inches)

Subgrade Modulus (1 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	274480	451090	604160	822110
250000	1431900	8310000	18290000	37666000
400000	2740000	19340000	44368000	93461000
750000	7121700	58046000	136270000	290170000
1000000	11041000	92856000	219370000	468970000
2000000	29428000	261390000	634990000	1388500000

Subgrade Modulus (5 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	2846500	5920000	8497600	12086000
250000	9691100	51309000	109210000	221540000
400000	17392000	112280000	255050000	545600000
750000	42096000	332700000	810330000	1838200000
1000000	63841000	543220000	1363100000	3175900000
2000000	167560000	1700000000	4647300000	11709000000

Subgrade Modulus (10 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	10486000	16928000	17546000	18087000
250000	24439000	127780000	268130000	534670000
400000	42320000	265940000	593530000	1246400000
750000	98503000	754400000	1807200000	4037200000
1000000	147300000	1218300000	3013300000	6931500000
2000000	378510000	3794700000	10283000000	25776000000

Subgrade Modulus (20 ksi)	ESAL			
Hb, mm (in)	101.6 (4)	203.2 (8)	254 (10)	304.8 (12)
Mr Base, psi				
20000	22530000	22530000	22530000	22530000
250000	67862000	354160000	679010000	801140000
400000	111250000	688540000	1525000000	3173400000
750000	244850000	1846900000	4392200000	9715100000
1000000	359380000	2942800000	7229900000	16463000000
2000000	899720000	9095400000	24494000000	60602000000

Table 6-6 Mr Models of Meridian Aggregate Stabilized with CKD, CFA, FBA, PC and Subjected to F-T/W-D Cycles

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CKD			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	110078	0.200	8.68E-02	0.77
	8	65358	0.080	1.64E-01	0.82
	16	43321	0.256	-1.02E-01	0.90
	30	---	---	---	---
No of W-D Cycles	0	110078	0.200	8.68E-02	0.77
	8	89557	0.089	1.64E-01	0.75
	16	54188	0.139	2.04E-01	0.68
	30	23105	0.201	3.05E-01	0.77

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CFA			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	180426	0.158	1.38E-01	0.89
	4	251536	0.060	1.25E-01	0.76
	12	353346	0.058	9.20E-02	0.83
	30	277013	0.137	0.0714	0.94
No of W-D Cycles	0	180426	0.158	0.1381	0.89
	4	173620	0.128	1.95E-01	0.76
	12	215080	0.190	9.50E-02	0.87
	30	178772	0.169	1.17E-01	0.85

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		FBA			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	337443	0.175	6.70E-02	0.61
	8	216870	0.136	1.28E-01	0.54
	16	94384	0.178	1.31E-01	0.83
	30	45238	0.201	0.129	0.85
No of W-D Cycles	0	337443	0.175	0.0670	0.61
	8	104472	0.141	4.15E-01	0.64
	16	114314	0.135	3.56E-01	0.66
	30	106023	0.098	3.57E-01	0.50

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		PC			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	526017	0.186	0.125	0.78
	8	465479	0.129	0.158	0.68
	16	285167	0.143	0.122	0.60
	30	178238	0.143	0.122	0.60
No of W-D Cycles	0	526017	0.186	0.125	0.78
	8	483949	0.123	0.250	0.82
	16	545632	0.096	0.154	0.65
	30	442486	0.127	0.138	0.62

Table 6-7 Mr Models of Richard Spur Aggregate Stabilized with CKD, CFA, and FBA and Subjected to F-T/W-D Cycles

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CKD			
Model Paramters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	281125	0.128	1.43E-01	0.73
	8	144677	0.344	3.76E-02	0.58
	16	119978	0.063	1.86E-01	0.60
	30	51892	0.275	-1.28E-01	0.92
No of W-D Cycles	0	281125	0.128	0.143	0.73
	8	234639	0.130	0.168	0.71
	16	172227	0.046	0.285	0.22
	30	155848	0.151	0.175	0.73

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CFA			
Model Paramters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	406724	0.069	0.130	0.53
	4	191029	0.145	0.109	0.91
	12	101088	0.270	0.122	0.72
	30	71796	0.158	0.036	0.91
No of W-D Cycles	0	406724	0.069	0.1297	0.53
	4	283792	0.159	0.106	0.61
	12	306902	0.182	0.020	0.95
	30	271394	0.153	0.052	0.84

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		FBA			
Model Paramters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	1057304	0.192	-9.27E-02	0.62
	8	674373	0.170	-1.01E-01	0.60
	16	198061	0.023	2.16E-01	0.60
	30	46291	0.127	0.385	0.67
No of W-D Cycles	0	1057304	0.192	-0.093	0.62
	8	941239	0.129	-0.038	0.89
	16	95918	0.590	0.155	0.80
	30	431519	0.199	0.034	0.75

Table 6-8 Mr Models of Sawyer Aggregate Stabilized with CKD, CFA, and FBA and Subjected to F-T/W-D Cycles

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CKD			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	189496	0.239	9.66E-02	0.91
	8	171989	0.167	6.34E-02	0.83
	16	85192	0.226	5.89E-02	0.84
	30	33443	0.225	6.99E-02	0.82
No of W-D Cycles	0	189496	0.239	0.097	0.91
	8	338532	0.179	0.050	0.79
	16	341271	0.264	-0.085	0.80
	30	189191	0.062	0.202	0.27

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CFA			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	949730	-0.331	0.193	0.80
	8	412857	0.007	0.078	0.04
	16	229298	0.181	0.020	0.94
	30	6425	0.190	0.856	0.95
No of W-D Cycles	0	949730	-0.331	0.1934	0.80
	8	115664	0.100	0.339	0.51
	16	48551	0.303	0.318	0.84
	30	49125	0.146	0.403	0.92

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		FBA			
Model Parameters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	370681	0.153	3.36E-02	0.76
	8	201280	-0.021	0.273	0.32
	16	120116	0.083	8.60E-02	0.51
	30	2892	0.210	0.829	0.88
No of W-D Cycles	0	370681	0.153	0.034	0.76
	8	40198	0.054	0.651	0.89
	16	17022	0.250	0.385	0.72
	30	---	---	---	---

Table 6-9 Mr Models of Hanson Aggregate Stabilized with CKD, and FBA and Subjected to F-T/W-D Cycles

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		CKD			
Model Paramters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	248714	0.109	4.25E-02	0.66
	8	60702	0.106	2.31E-01	0.77
	16	12776	0.252	3.51E-01	0.90
	30	12028	0.278	8.88E-02	0.94
No of W-D Cycles	0	248714	0.109	0.043	0.66
	8	133906	0.082	0.189	0.70
	16	86497	0.205	0.144	0.68
	30	102778	0.063	0.176	0.76

$Mr = k_1 \times S_d^{k2} \times S_3^{k3}$

Stabilizing Agent --->		FBA			
Model Paramters --->		k_1	k_2	k_3	R^2
No of F-T Cycles	0	289468	0.089	1.00E-01	0.58
	8	30733	0.271	0.501	0.87
	16	---	---	---	---
	30	4931	0.249	0.928	0.98
No of W-D Cycles	0	289468	0.089	0.100	0.58
	8	201651	0.167	0.061	0.75
	16	---	---	---	---
	30	22977	0.170	0.627	0.85

Table 6-10 ESAL as a Function of Resilient Modulus for a 6-inch AC Layer

$$ESAL = m_1 + m_2 \times M_r + m_3 \times M_r^2 + m_4 \times M_r^3$$

Eac = 450 ksi; Hac = 6 in

Subgrade Modulus, (ksi)			**1**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	284	0.028	2.41E-07	-5.29E-04
8	41000	-0.513	6.08E-06	-6.50E-13
10	8880	-0.775	1.77E-05	2.41E-13
12	7020	-3.670	5.26E-05	3.48E-12
Subgrade Modulus, (ksi)			**5**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	12400	0.218	1.80E-06	-3.66E-13
8	182000	-1.950	3.70E-05	-2.47E-12
10	229000	-4.570	1.07E-06	7.47E-12
12	394000	-12.600	2.71E-04	6.73E-11
Subgrade Modulus, (ksi)			**10**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	61900	0.6490	4.13E-06	-7.60E-13
8	211000	1.2900	7.68E-05	-9.93E-14
10	492000	-3.9100	2.37E-04	2.67E-11
12	735000	-18.2000	6.16E-04	1.62E-10
Subgrade Modulus, (ksi)			**20**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	479000	1.28	1.11E-05	-2.07E-12
8	451000	12.50	1.80E-04	6.04E-12
10	226000	18.80	5.51E-04	8.62E-11
12	-446000	9.99	1.46E-03	4.24E-10
Eac : Modulus of AC layer				
Hac : Thickness of AC layer				

Table 6-11 ESAL as a Function of Resilient Modulus for a 9-inch AC Layer

$$ESAL = m_1 + m_2 \times M_r + m_3 \times M_r^2 + m_4 \times M_r^3$$

Eac = 450 ksi; Hac = 9 in

Subgrade Modulus, (ksi)			**1**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	17400	0.314	1.99E-06	-4.30E-13
8	12200	0.730	2.82E-05	-4.80E-12
10	70700	0.345	7.92E-05	-1.13E-11
12	208000	-1.190	1.95E-04	-2.33E-11
Subgrade Modulus, (ksi)			**5**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	246000	2.670	1.18E-05	-2.50E-12
8	392000	9.490	1.53E-04	-1.80E-11
10	597000	8.410	4.23E-04	-2.07E-11
12	1200000	-10.800	1.04E-03	3.46E-11
Subgrade Modulus, (ksi)			**10**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	1110000	5.7800	2.82E-05	-5.94E-12
8	2730000	26.1000	3.47E-04	-3.67E-11
10	2180000	44.3000	9.34E-04	-3.23E-11
12	1450000	48.3000	2.25E-03	1.13E-10
Subgrade Modulus, (ksi)			**20**	
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	4490000	146.00	6.80E-05	-1.43E-11
8	1780000	140.00	7.48E-04	-5.16E-11
10	-904000	257.00	2.08E-03	-1.29E-12
12	-28300000	138.00	5.60E-03	2.11E-10
Eac : Modulus of AC layer				
Hac : Thickness of AC layer				

Table 6-12 ESAL as a Function of Resilient Modulus for a 12-inch AC Layer

$$ESAL = m_1 + m_2 \times M_r + m_3 \times M_r^2 + m_4 \times M_r^3$$

Eac = 450 ksi; Hac = 12 in

Subgrade Modulus, (ksi)	**1**			
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	214000	1.38	1.08E-05	-2.35E-12
8	34300	9.28	1.07E-04	-2.32E-11
10	399000	18.80	2.55E-04	-5.25E-11
12	1400000	38.20	5.40E-04	-1.06E-10
Subgrade Modulus, (ksi)	**5**			
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	2400000	16.50	5.72E-05	-1.21E-11
8	3990000	56.40	5.72E-04	-8.81E-11
10	5410000	70.30	1.45E-03	-1.64E-10
12	8120000	41.00	3.36E-03	-2.26E-10
Subgrade Modulus, (ksi)	**10**			
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	9390000	31.80	1.37E-04	-3.04E-11
8	11500000	188.00	1.19E-03	-1.69E-10
10	8130000	330.00	2.95E-03	-2.75E-10
12	3930000	469.00	6.72E-03	-2.56E-10
Subgrade Modulus, (ksi)	**20**			
Base Thickness, (in)	m_1	m_2	m_3	m_4
4	19400000	135.00	2.59E-04	-5.30E-11
8	6230000	793.00	2.41E-03	-2.69E-10
10	-16300000	1330.00	6.39E-03	-4.63E-10
12	-126000000	1210.00	1.64E-02	-9.00E-10
Eac : Modulus of AC layer				
Hac : Thickness of AC layer				

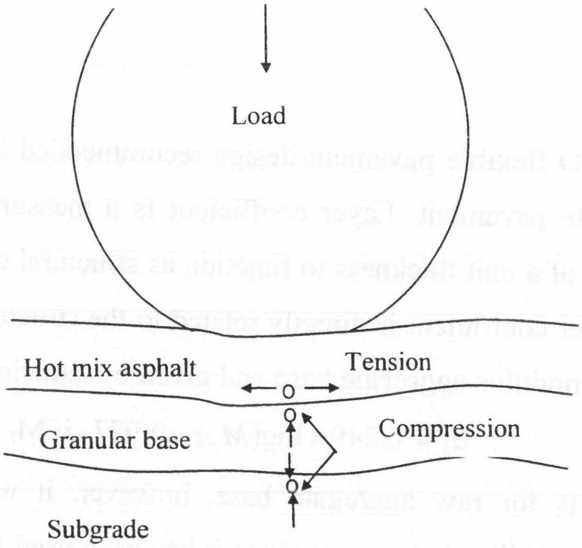


Figure 6-1 Tensile and Compressive Strains in Flexible Pavements (after Huang, 1993).

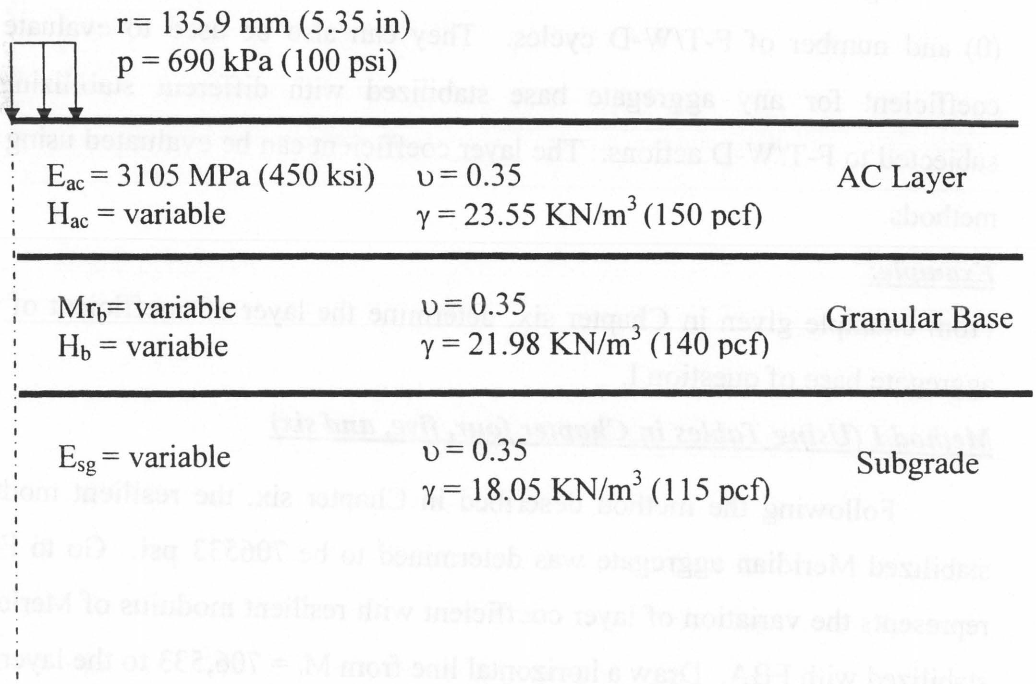


Figure 6-2 Problem Descriptions (Single-Wheel, with Three Layers Pavement Structure).

7.1 General

AASHTO flexible pavement design recommended the use of layer coefficient in design a flexible pavement. Layer coefficient is a measure of the relative ability of a given materials of a unit thickness to function as structural component of pavement (Zhu, 1998). The layer coefficient is directly related to the structural number. It is also related to the resilient modulus aggregate base and given by equation 7.1:

$$a_2 = 0.249 \times \log(M_r) - 0.977 \quad \text{if } M_r \text{ units is in psi.}$$

This equation is for raw aggregate base, however, it will be used in this study to determine a_2 of stabilized aggregate since it has been used by other researches (Zaman et al. 1998, Zhu, 1998; Pandey, 1996).

7.2 Results

Figures 7-1 to 7-24 illustrates the variation of resilient modulus with bulk stress (θ) and number of F-T/W-D cycles. They can also be used to evaluate the layer of coefficient for any aggregate base stabilized with different stabilizing agents and subjected to F-T/W-D actions. The layer coefficient can be evaluated using two different methods.

Example:

From example given in Chapter six, determine the layer of coefficient of the stabilized aggregate base of question I.

Method I (Using Tables in Chapter four, five, and six)

Following the method described in Chapter six, the resilient modulus of FBA-stabilized Meridian aggregate was determined to be 706533 psi. Go to Figure 7-5 that represents the variation of layer coefficient with resilient modulus of Meridian aggregate stabilized with FBA. Draw a horizontal line from M_r = 706,533 to the layer of coefficient (a_2) curve. The projection of the intersection of both the horizontal line and the layer of coefficient curve to the x-axis define the layer of coefficient. In this case, a_2 is equal to 0.48.

Method II (Using Tables in this Chapter)

Given S_d = 20 psi, and S_3 = 10 psi, thus, the bulk stress is approximately 50 psi. Using Figure 7-5, draw a vertical line from θ = 50 psi to the curve of 0 F-T cycles. From the intersection, draw a horizontal line to the a_2 curve. The layer of coefficient is the projection of the last point to the x-axis, and it is approximately 0.482.

It is interesting to mention that there are many different ways to present and use the aforementioned results. However, no efforts were made to develop other models and graphs.

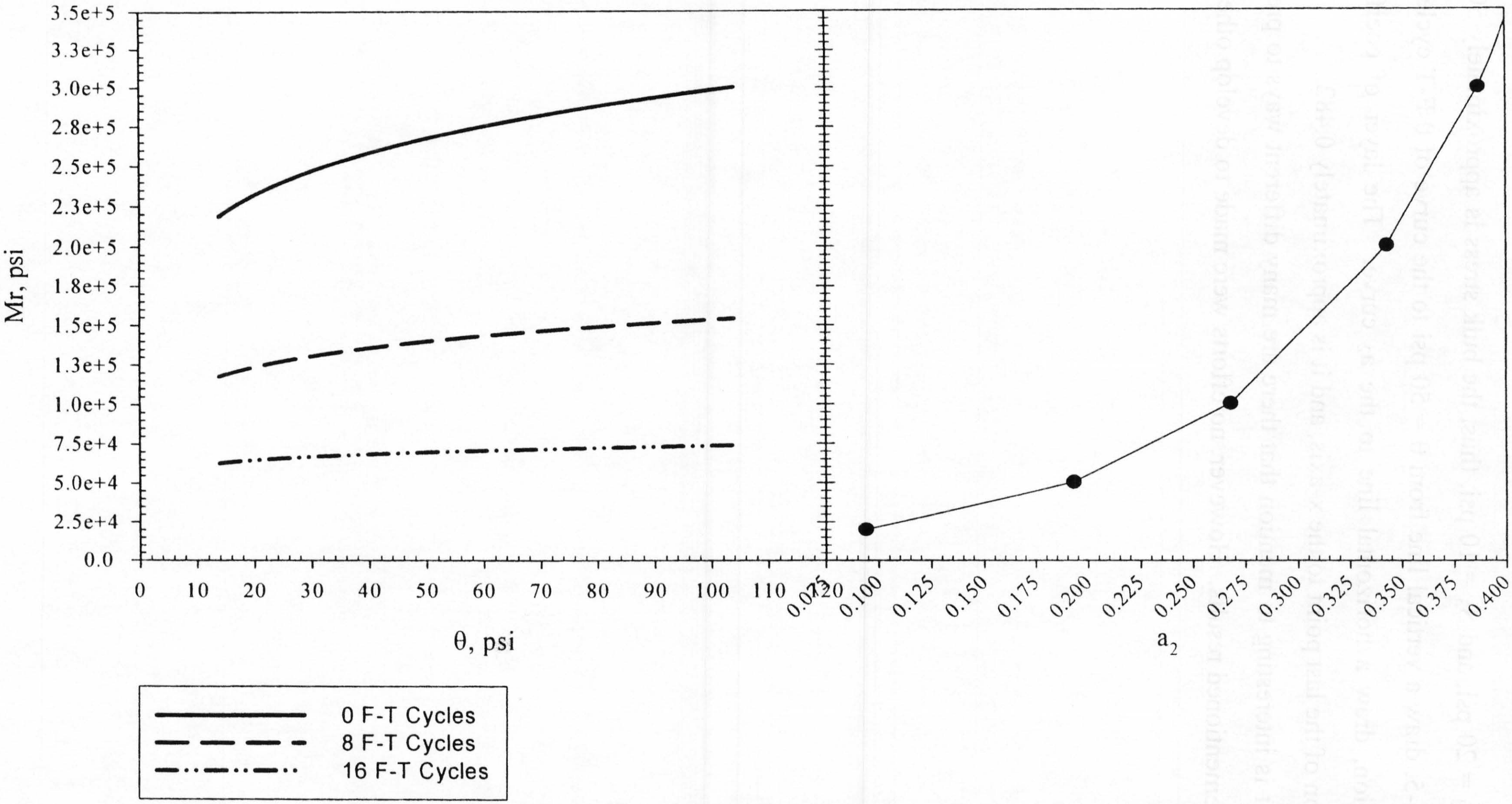


Figure 7-1 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Meridian CKD-Stabilized Aggregate

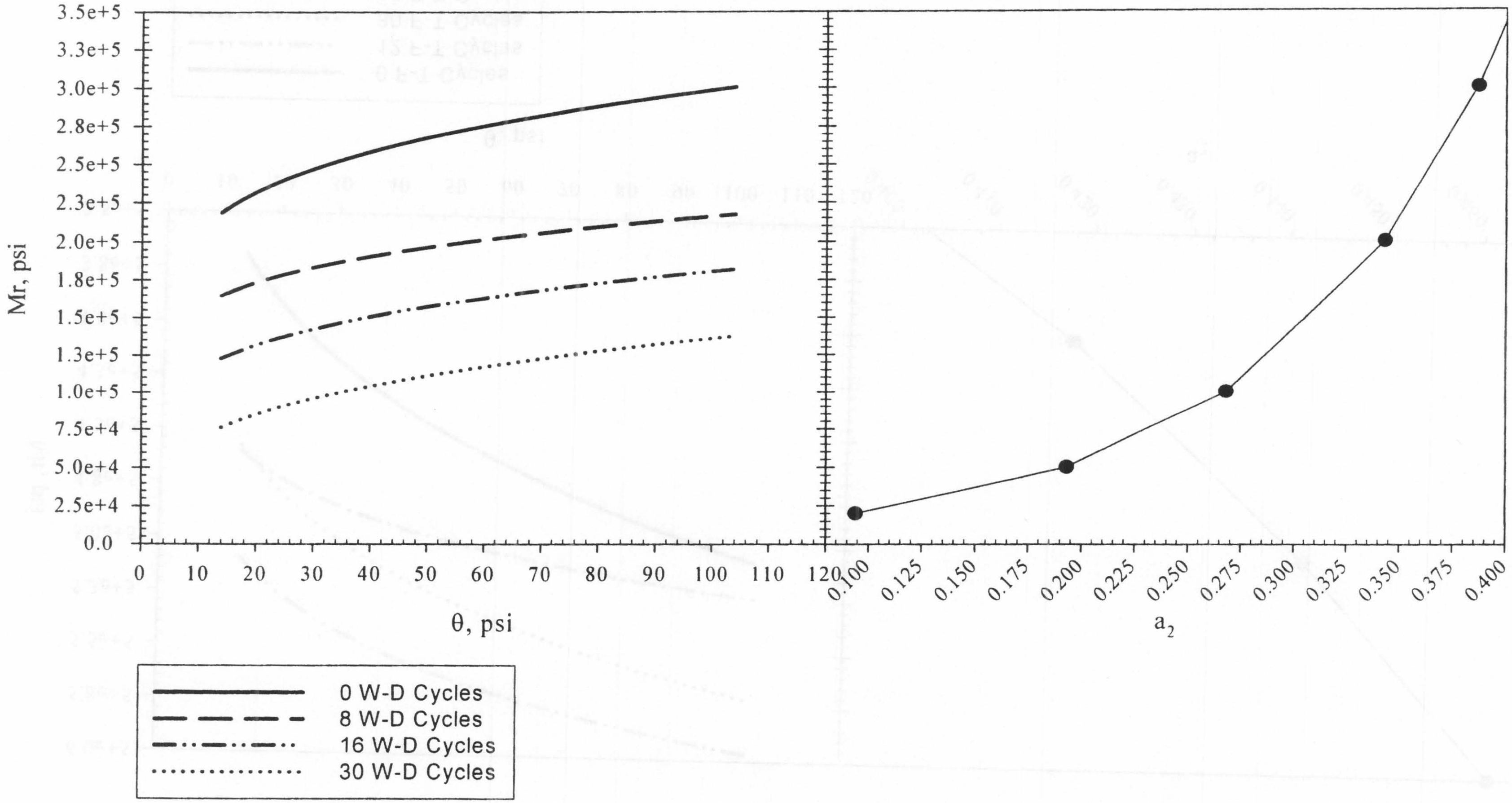


Figure 7-2 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Meridian CKD-Stabilized Aggregate

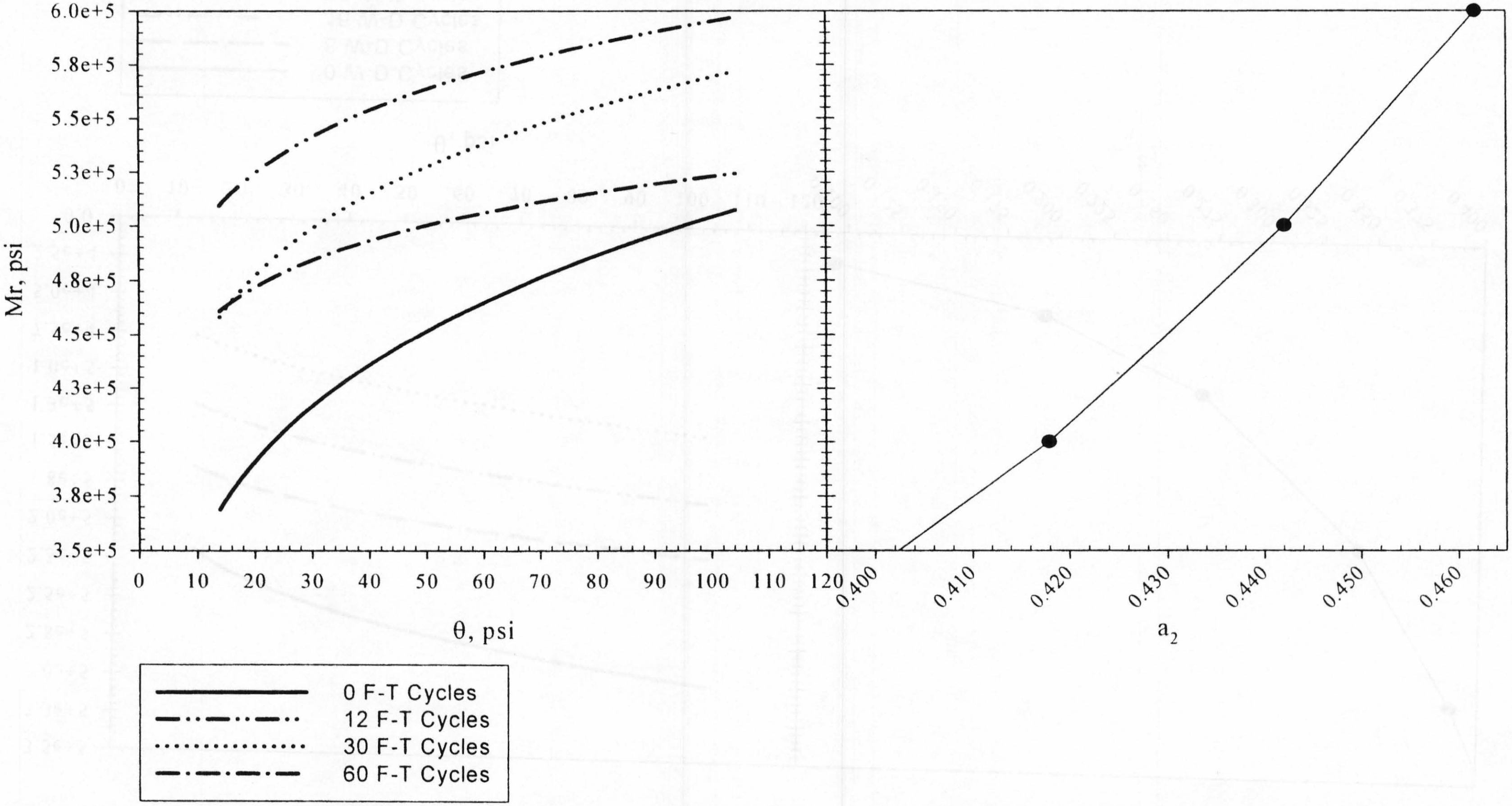


Figure 7-3 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Meridian CFA-Stabilized Aggregate

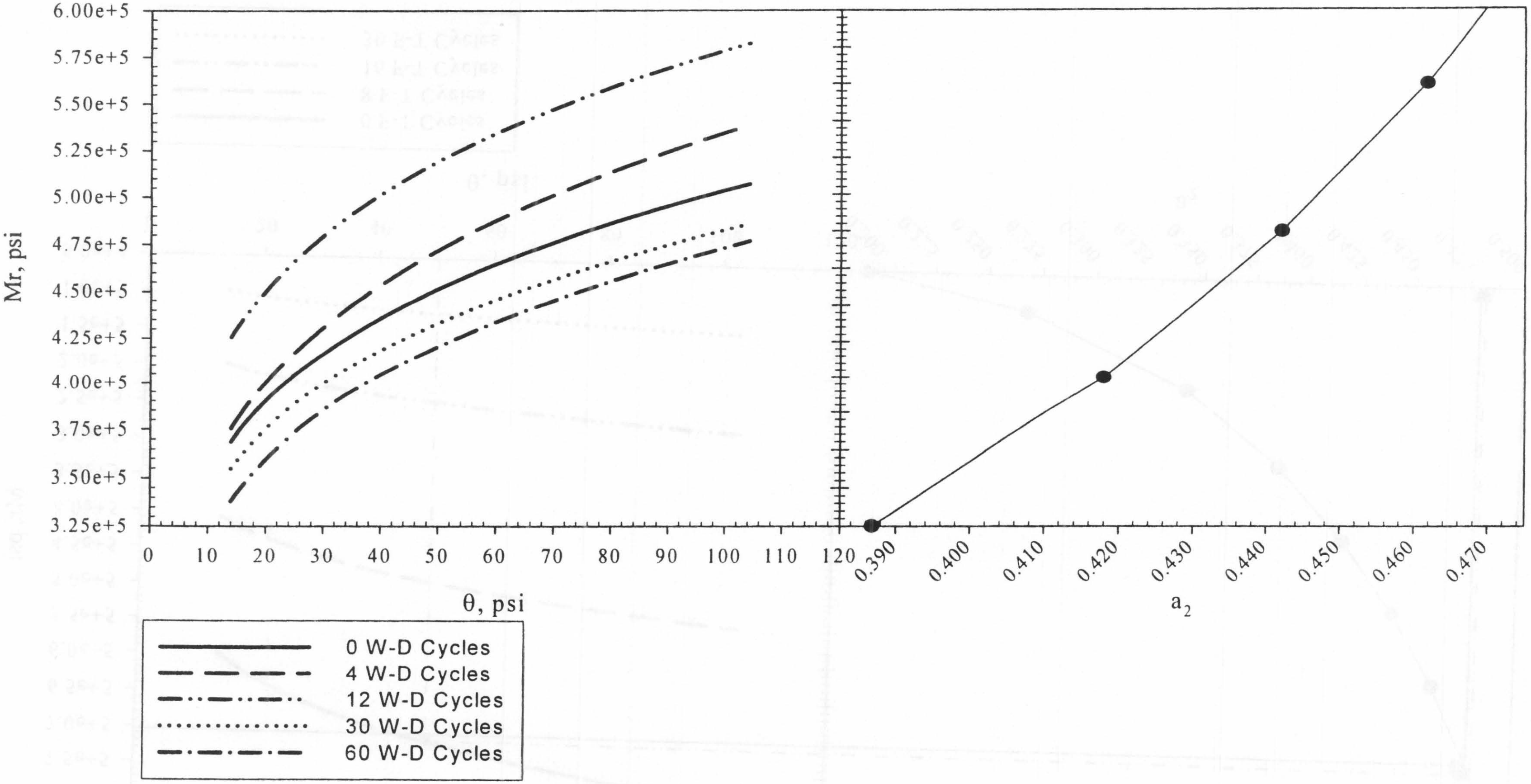


Figure 7-4 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Meridian CFA-Stabilized Aggregate

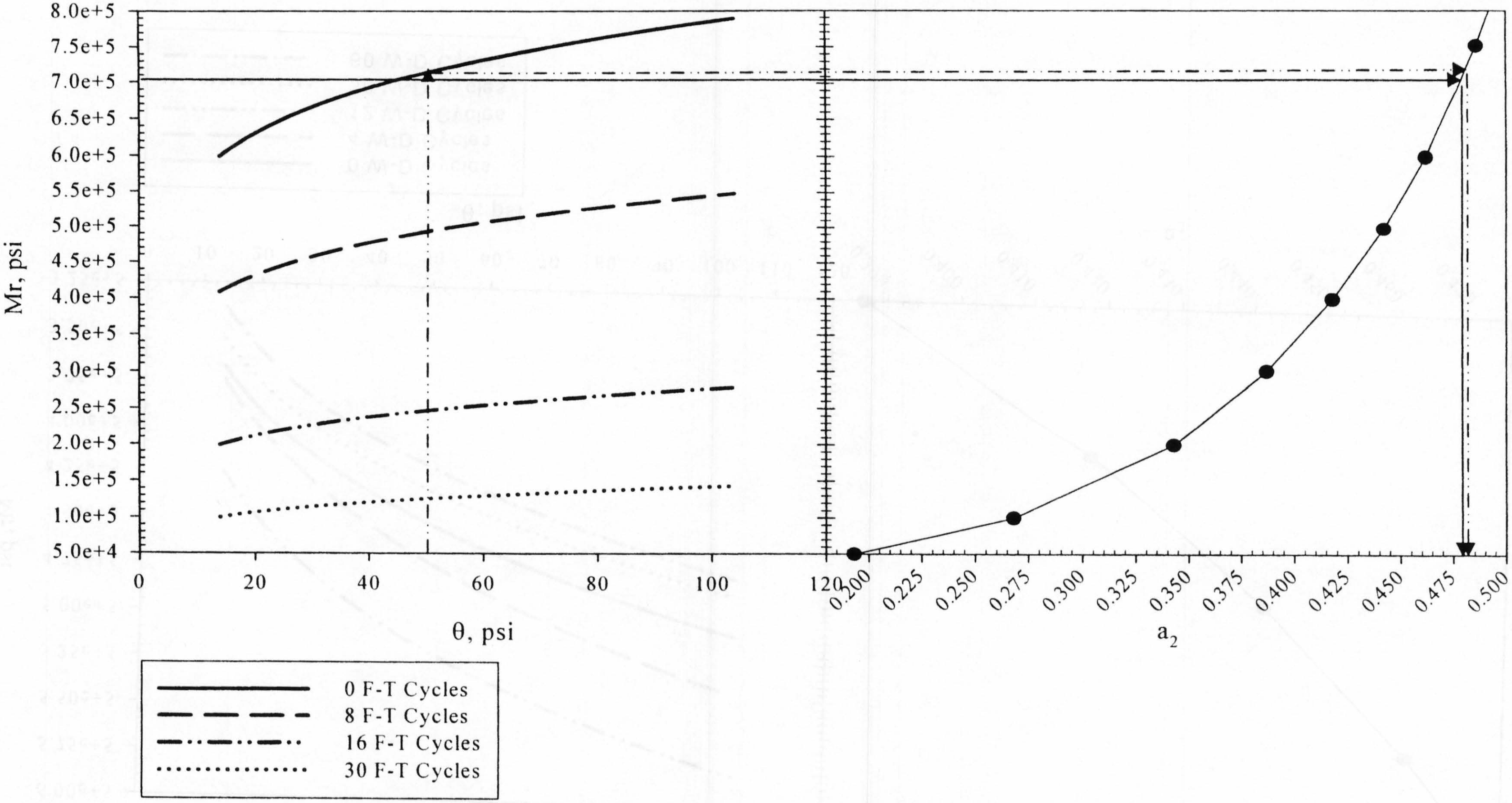


Figure 7-5 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Meridian FBA-Stabilized Aggregate

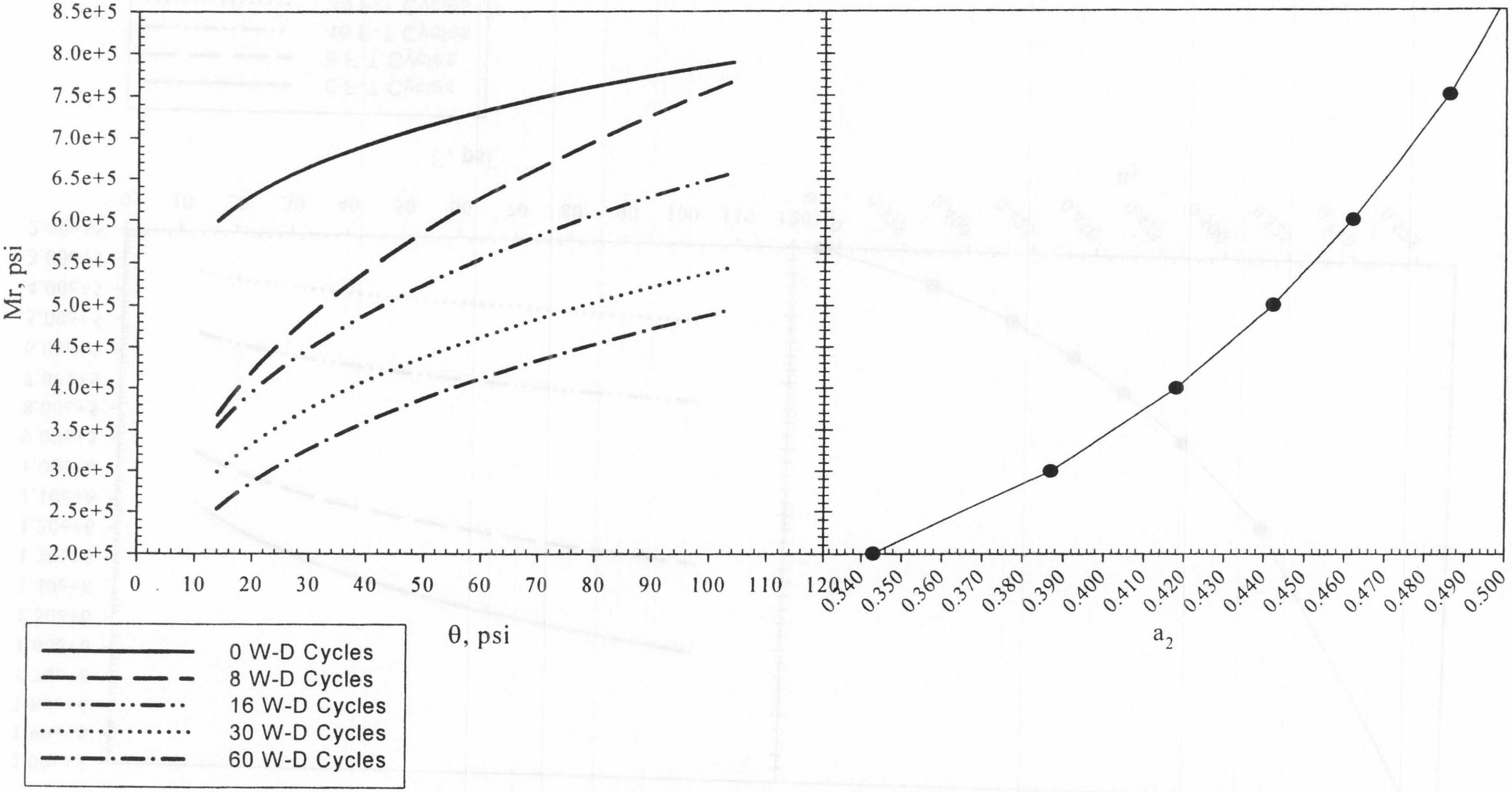


Figure 7-6 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Meridian FBA-Stabilized Aggregate

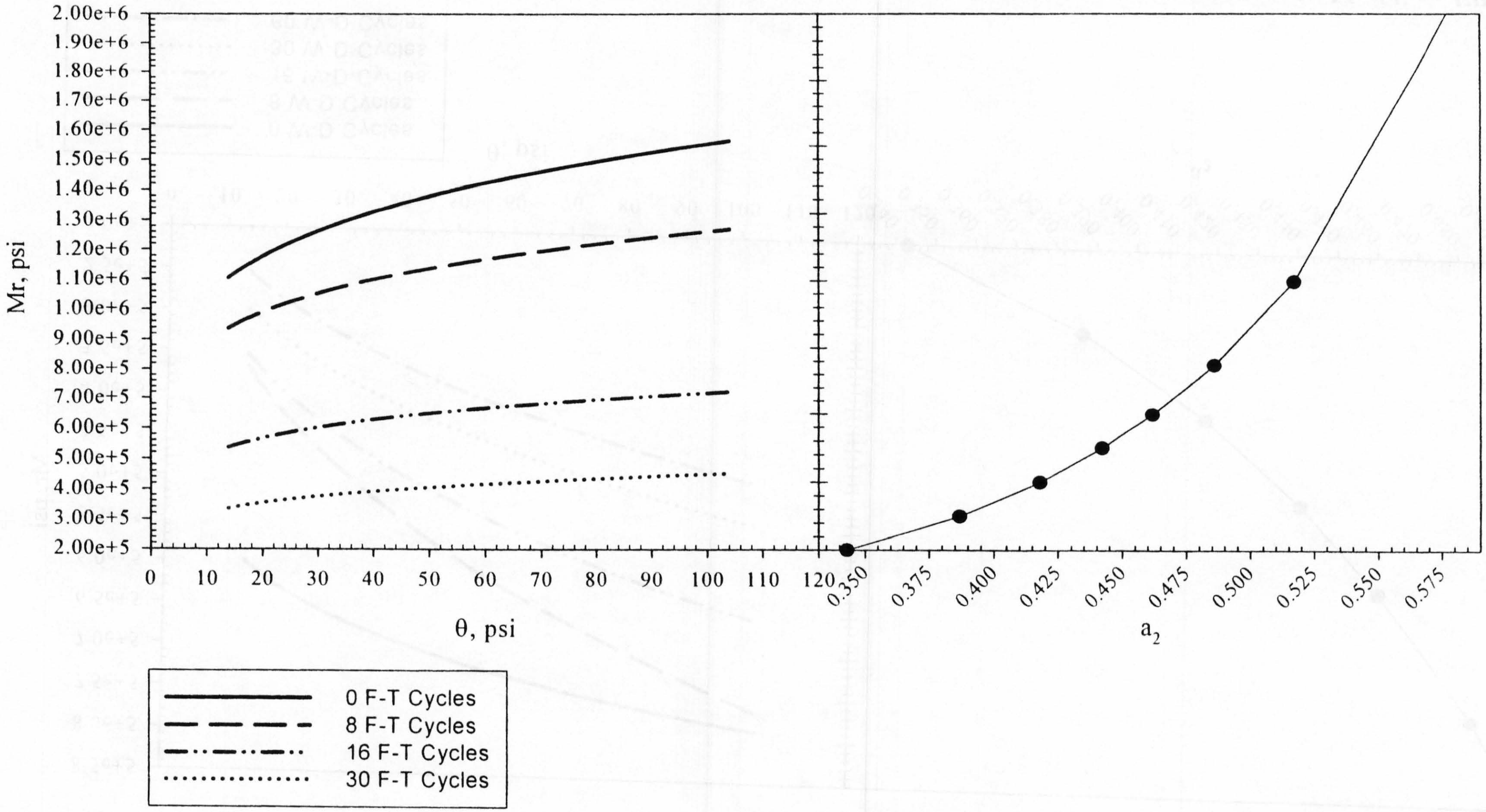


Figure 7-7 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Meridian PC-Stabilized Aggregate

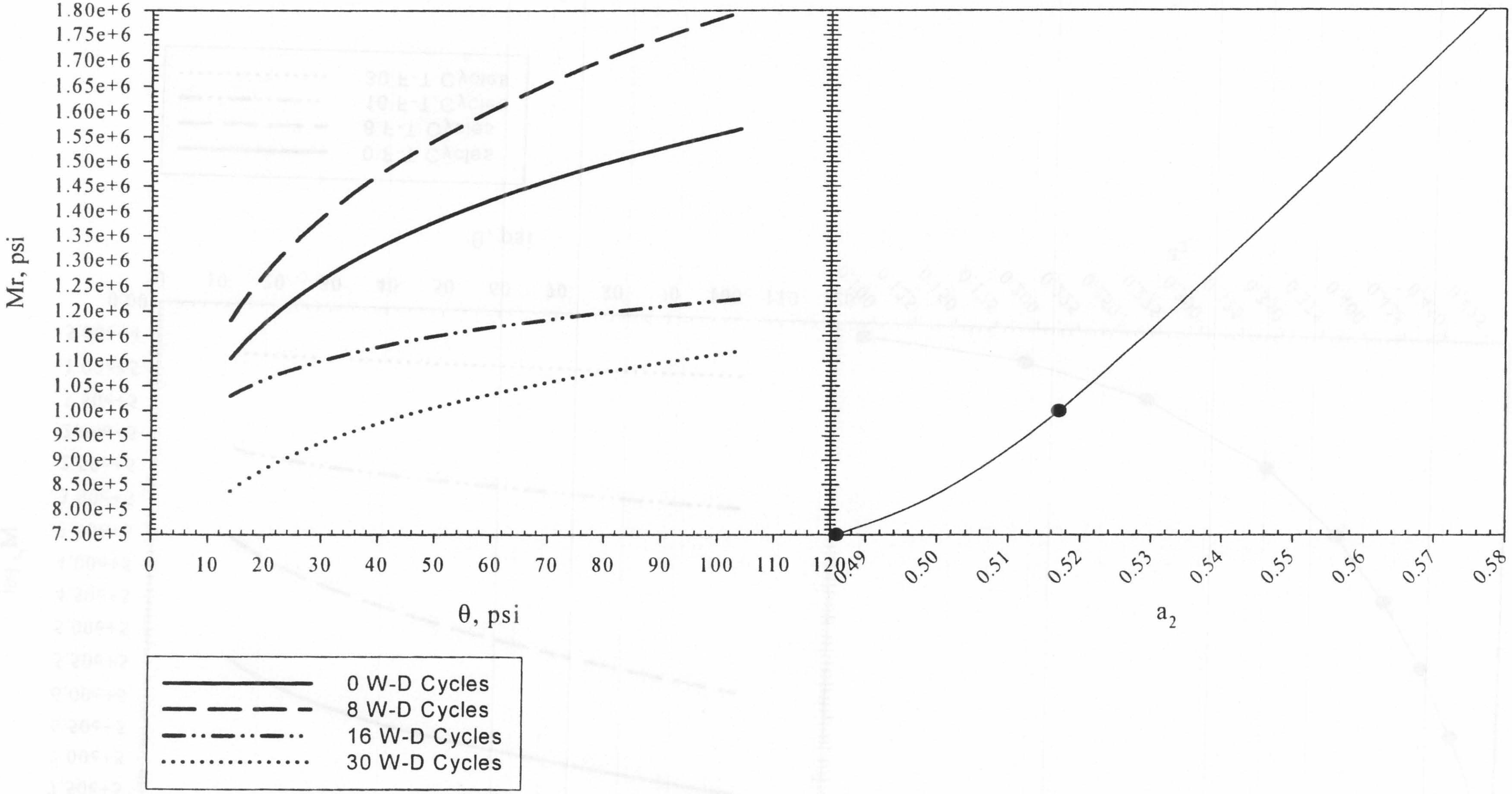


Figure 7-8 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Meridian PC-Stabilized Aggregate

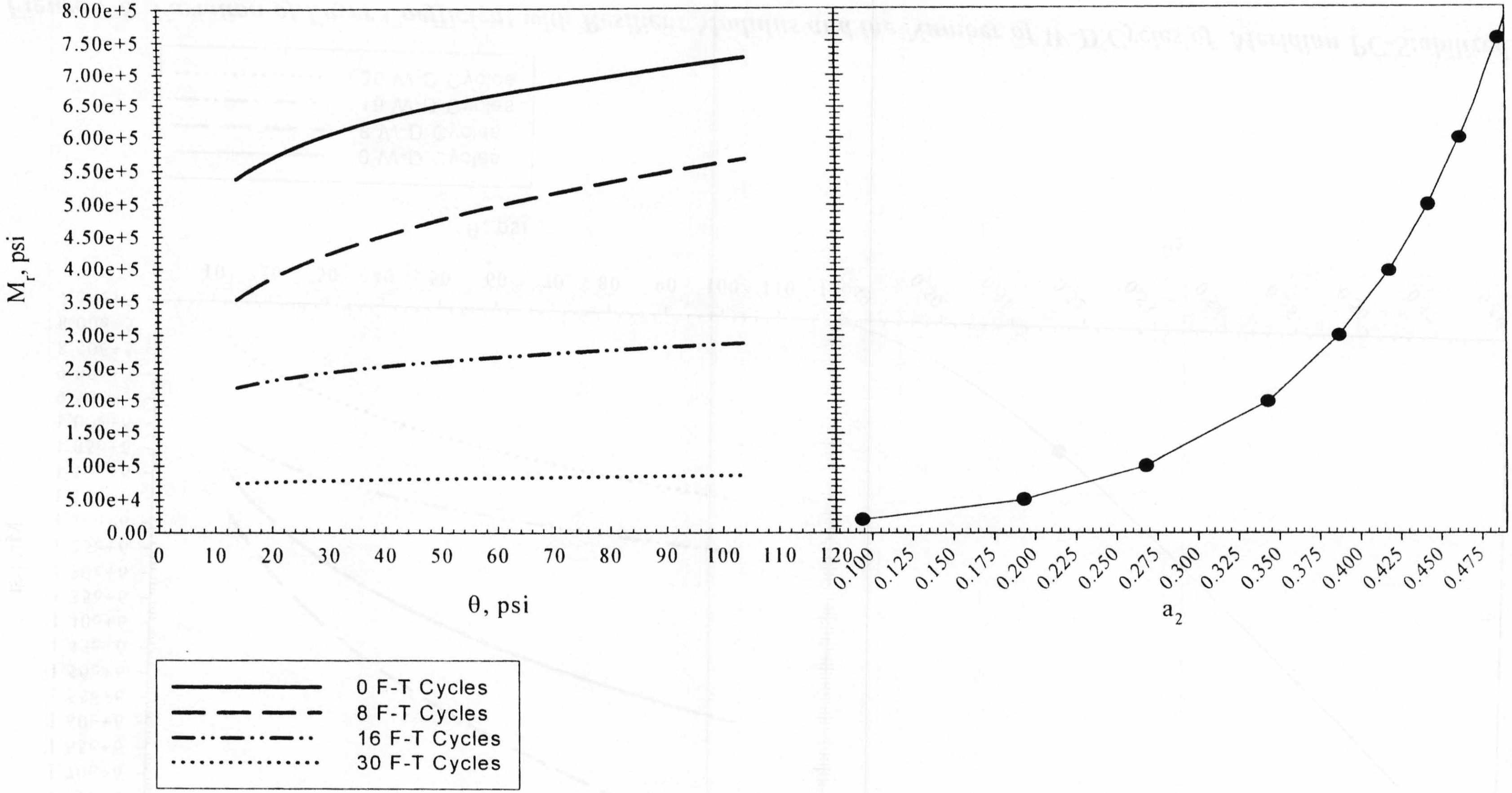


Figure 7-9 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Richard Spur CKD-Stabilized Aggregate

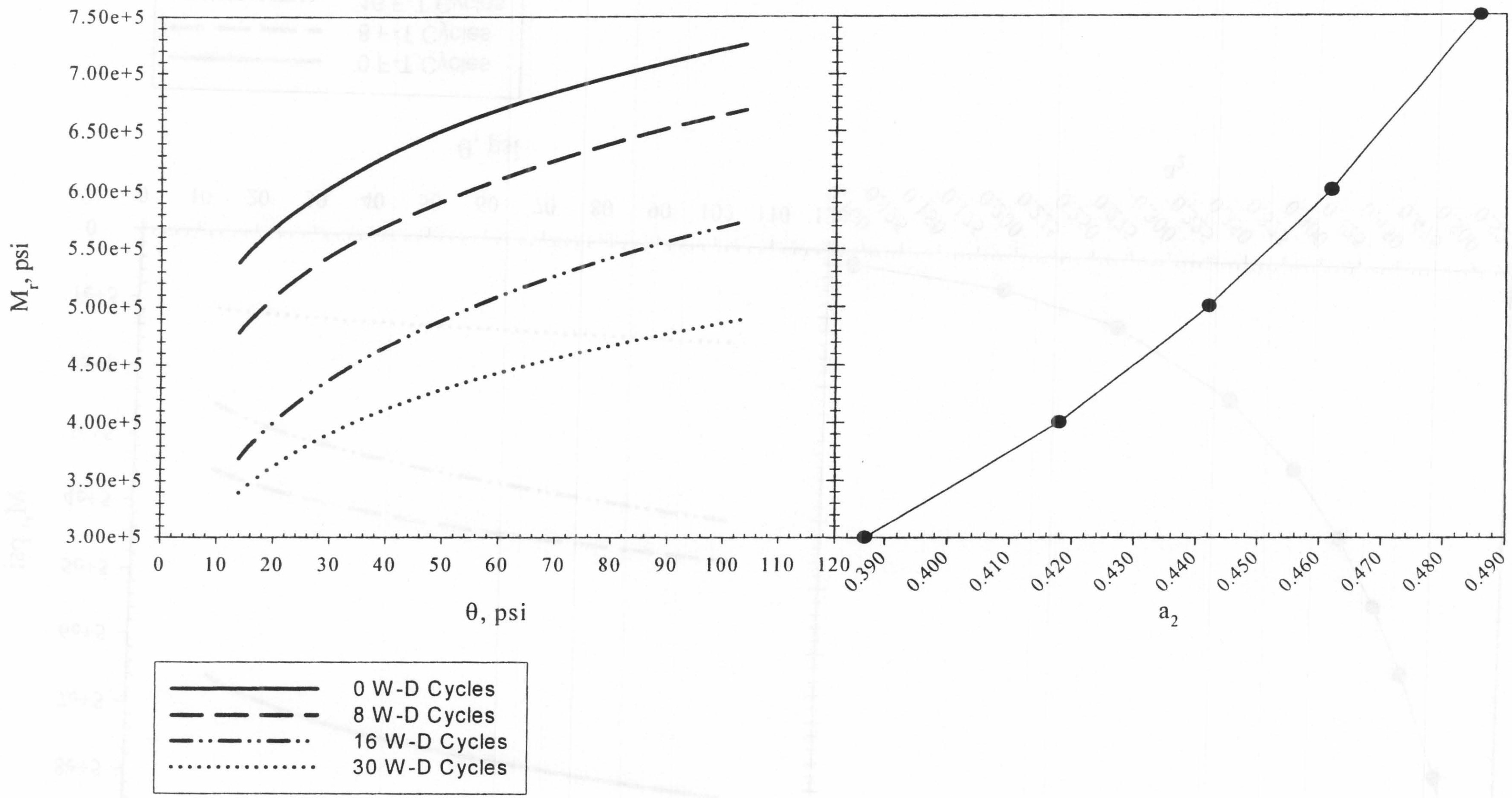


Figure 7-10 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Richard Spur CKD-Stabilized Aggregate

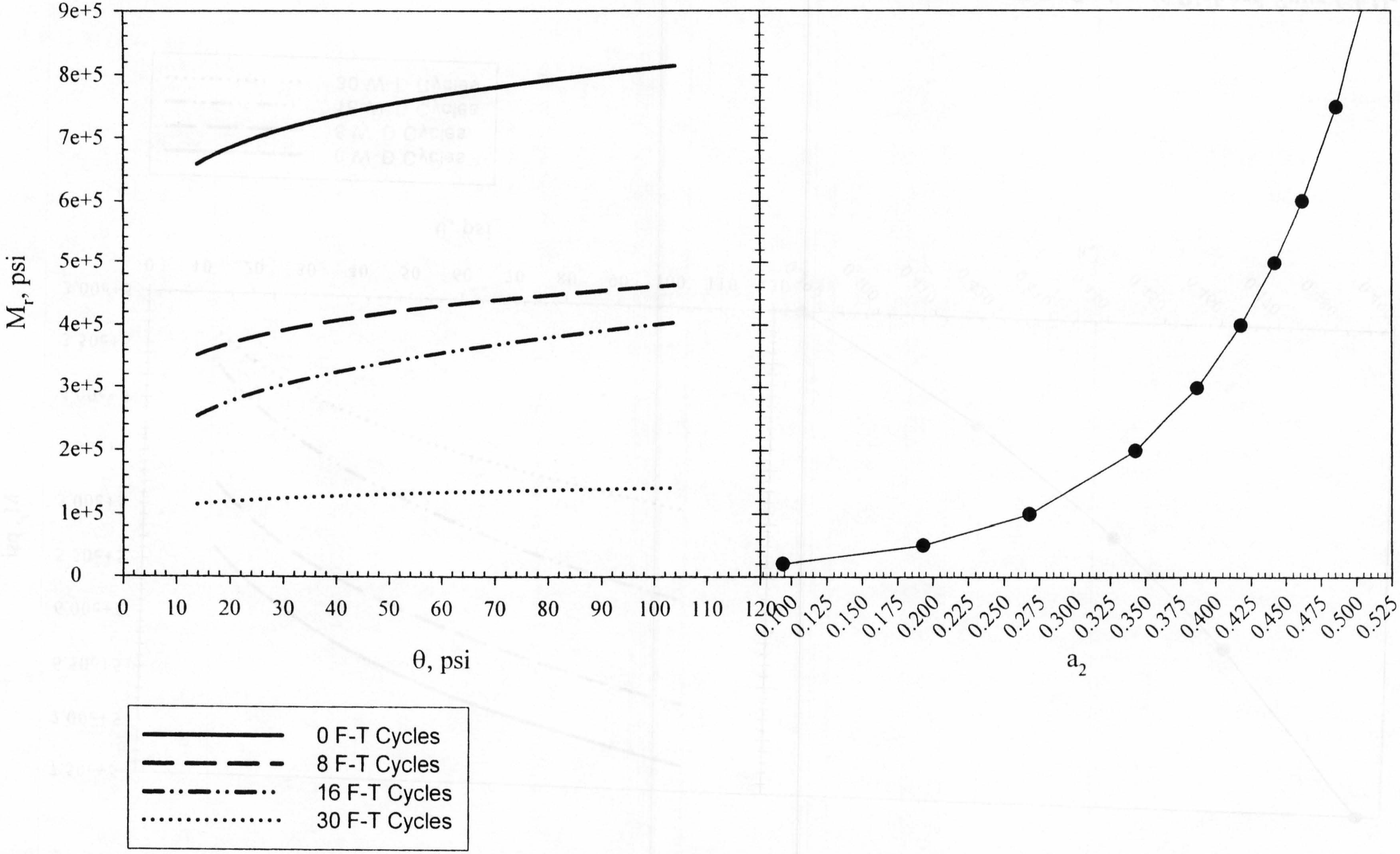


Figure 7-11 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Richard Spur CFA-Stabilized Aggregate

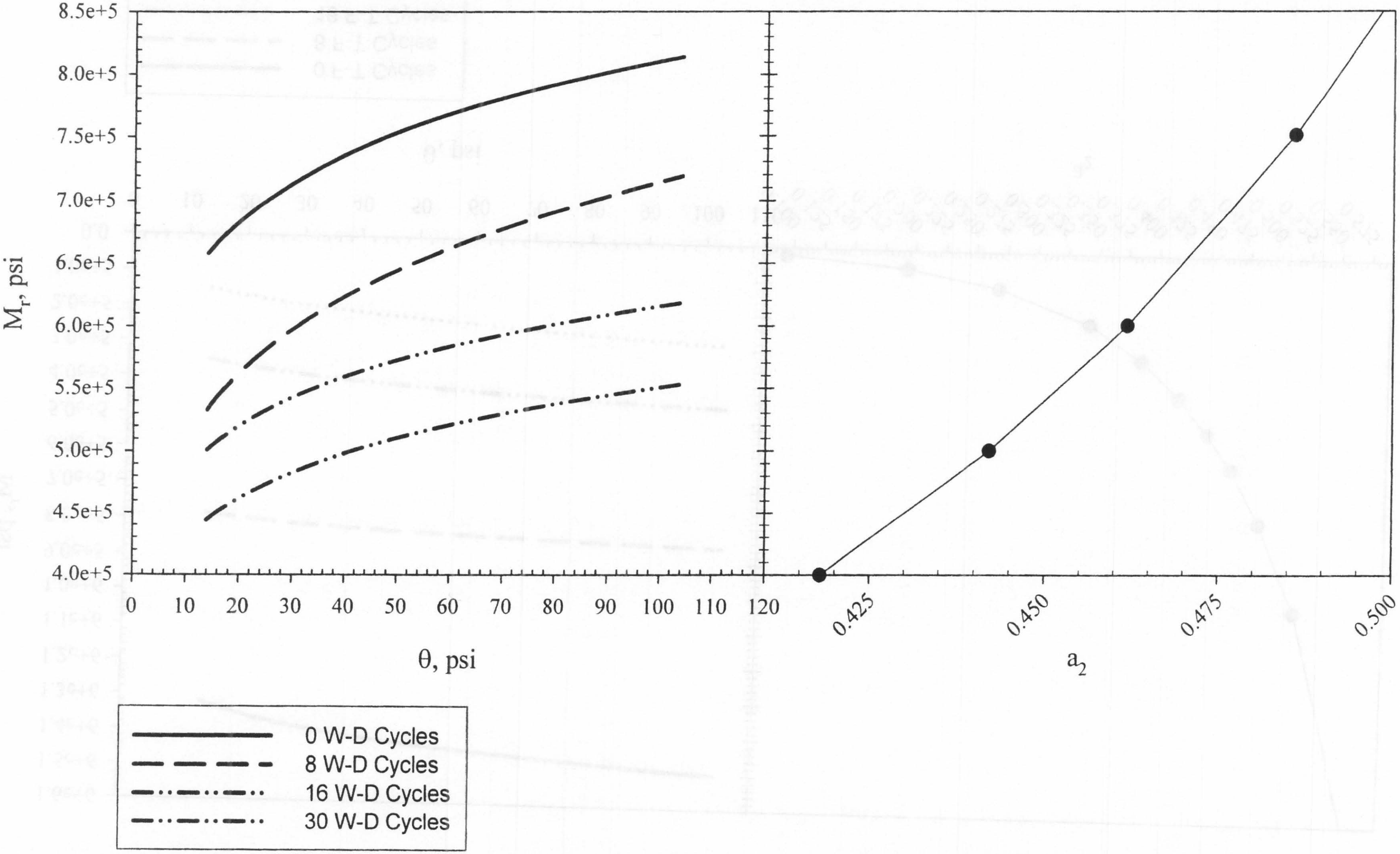


Figure 7-12 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Richard Spur CFA-Stabilized Aggregate

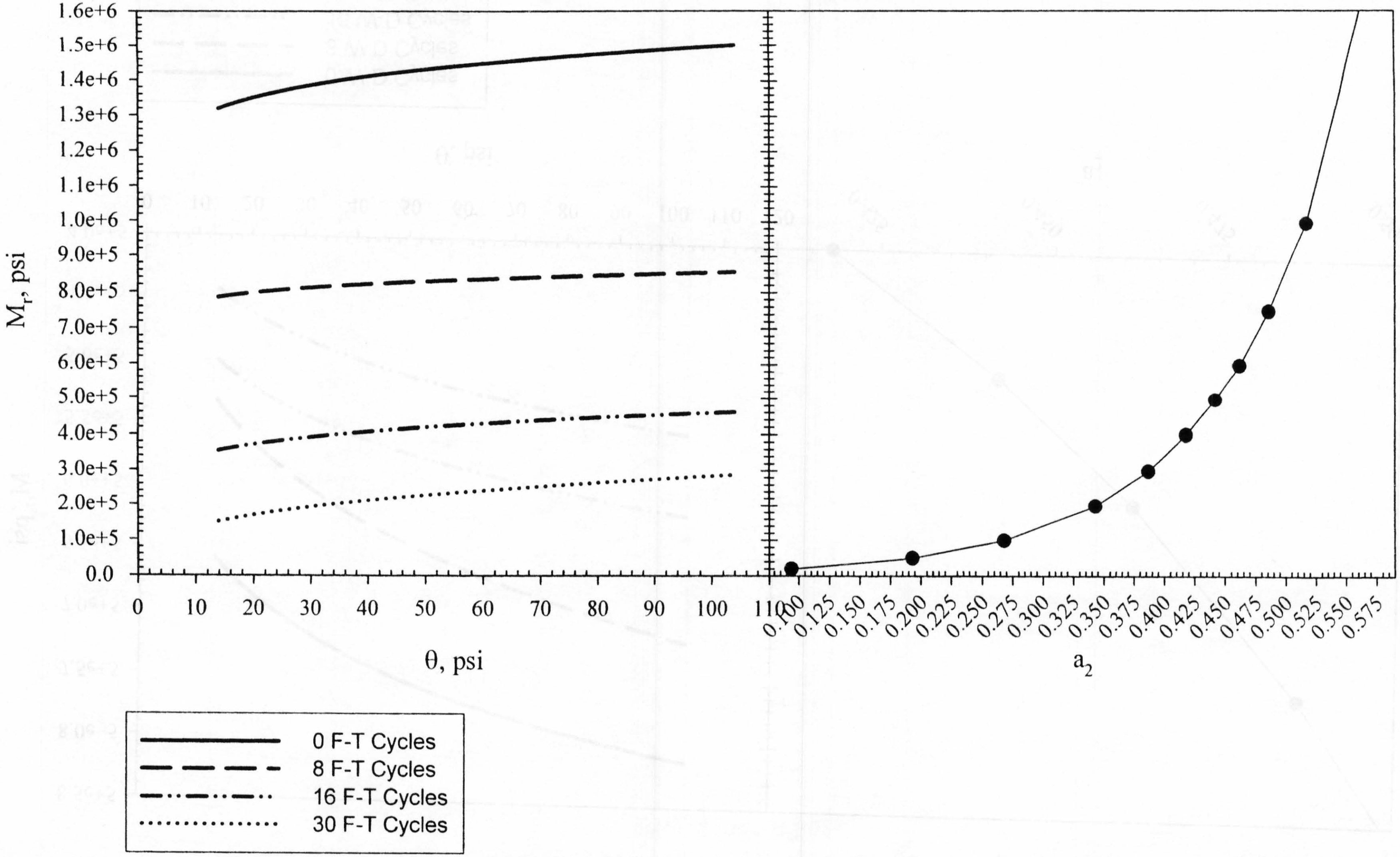


Figure 7-13 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Richard Spur FBA-Stabilized Aggregate

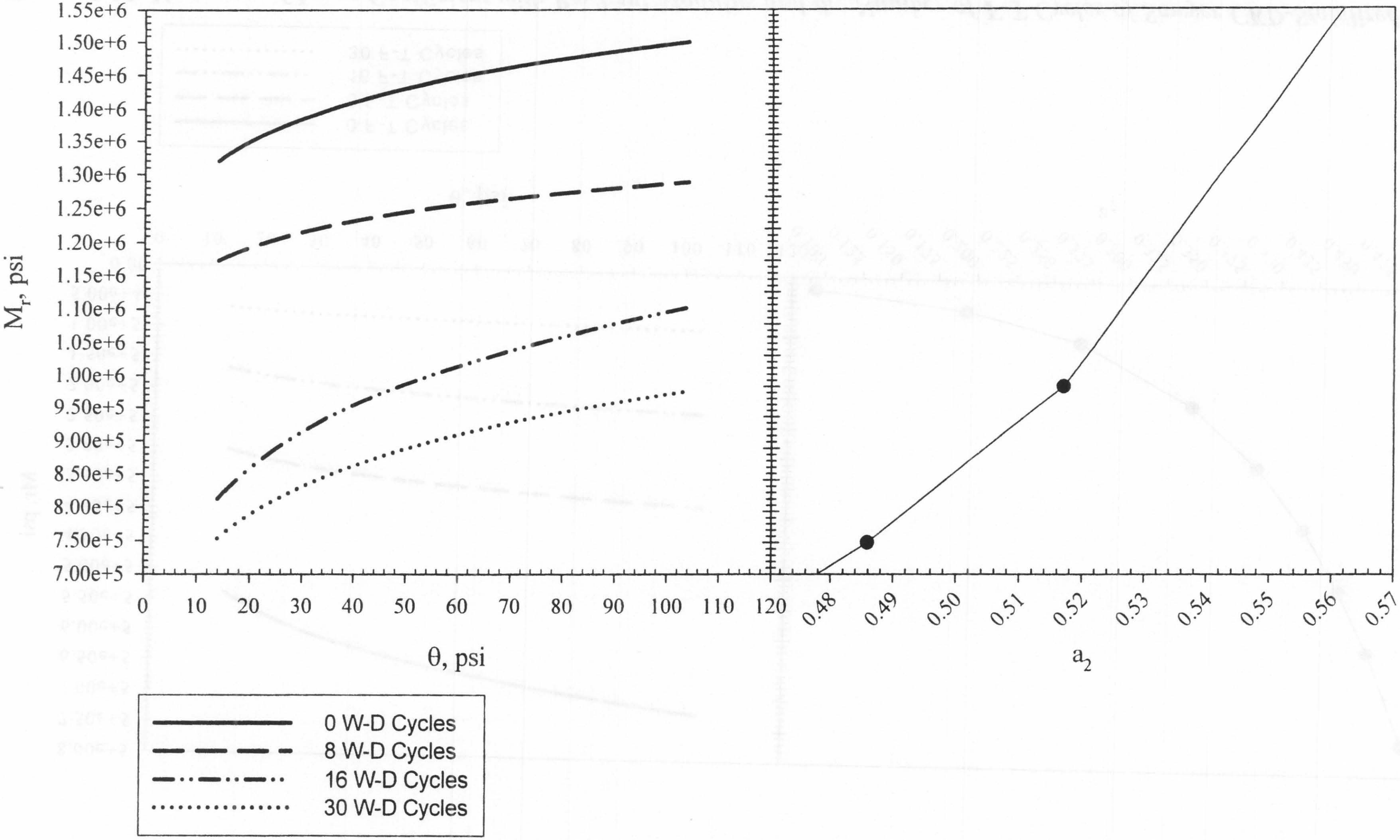


Figure 7-14 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Richard Spur FBA-Stabilized Aggregate

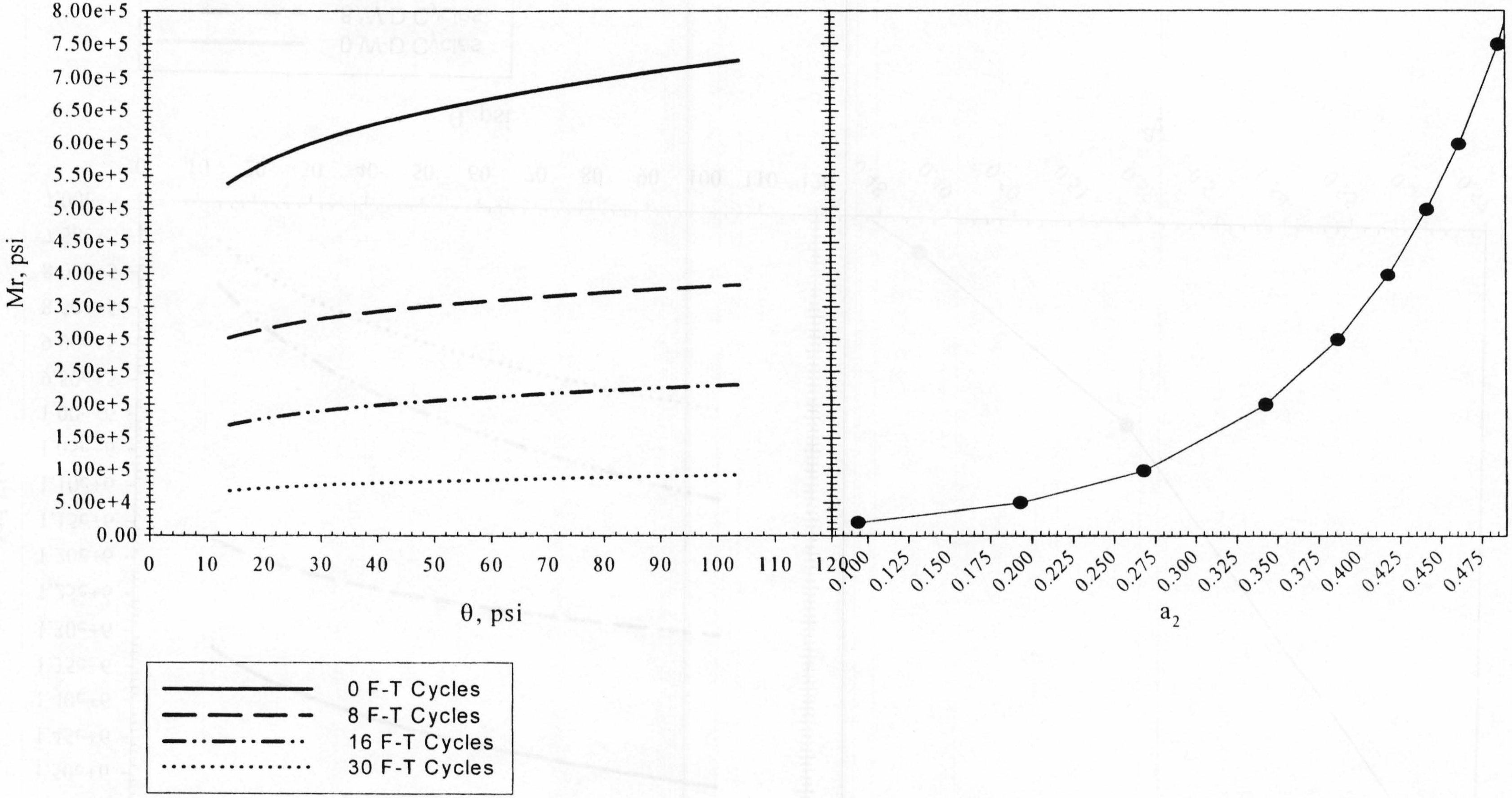


Figure 7-15 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Sawyer CKD-Stabilized Aggregate

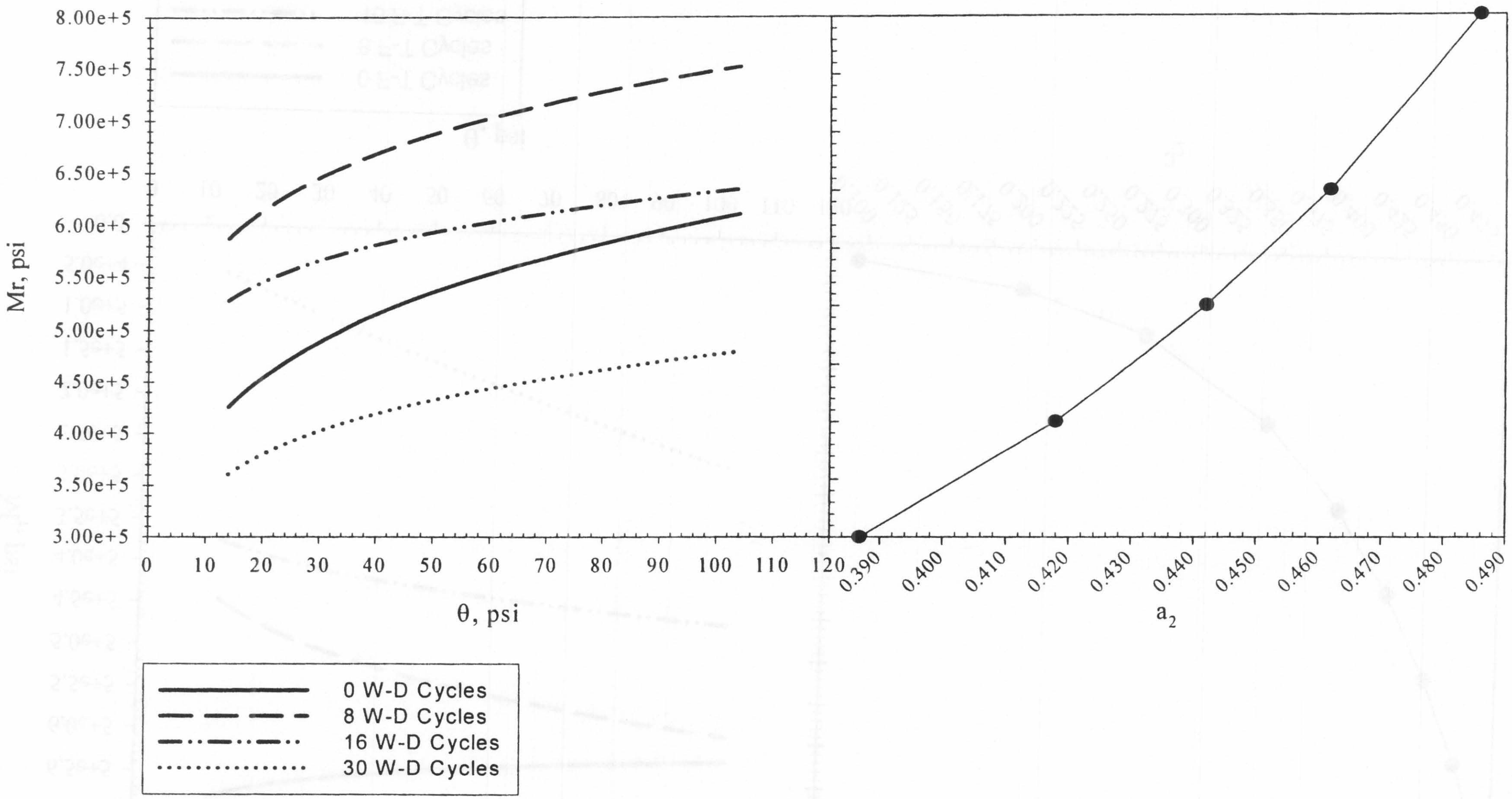


Figure 7-16 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Sawyer CKD-Stabilized Aggregate

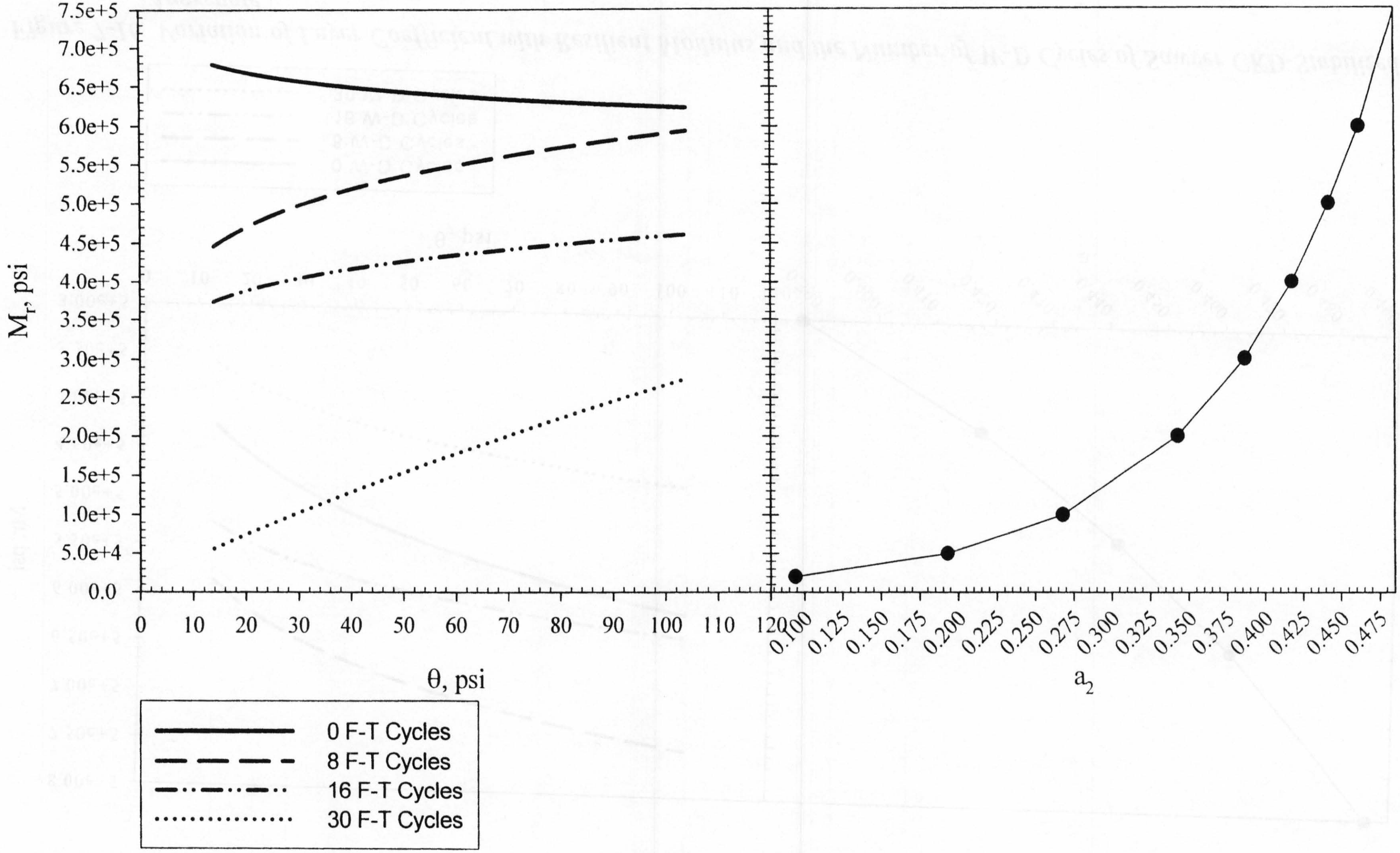


Figure 7-17 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Sawyer CFA-Stabilized Aggregate

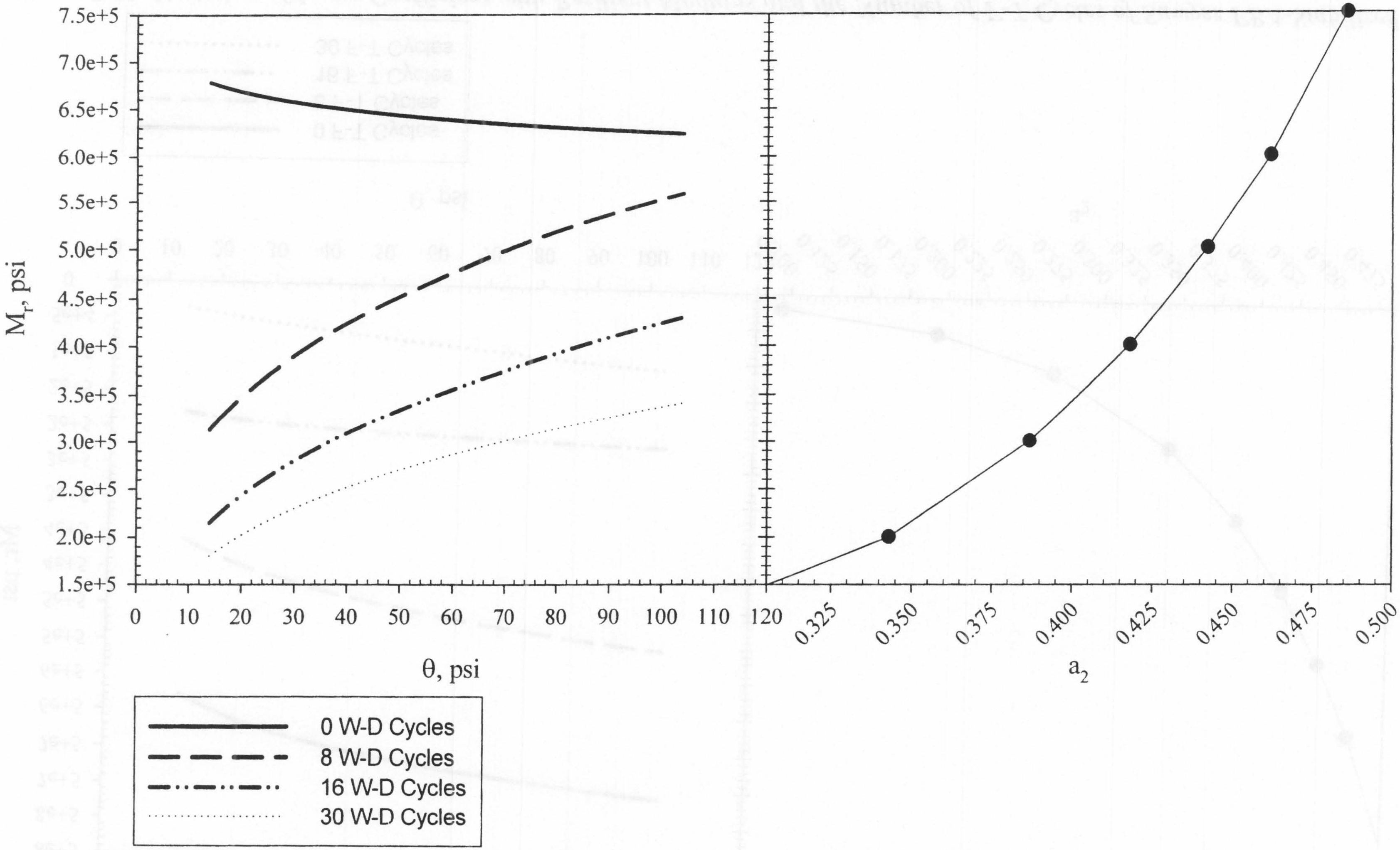


Figure 7-18 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Sawyer CFA-Stabilized Aggregate

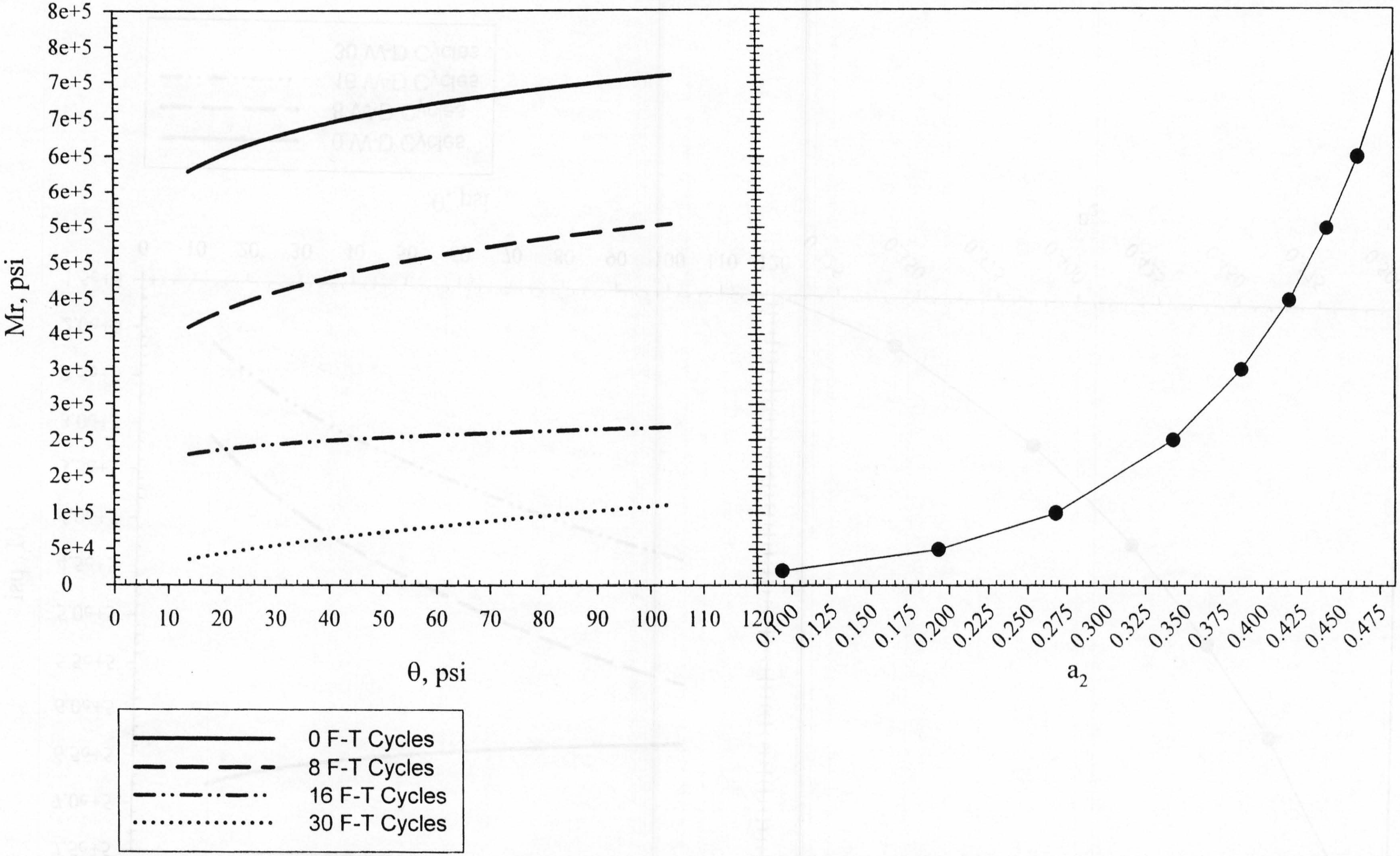


Figure 7-19 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Sawyer FBA-Stabilized Aggregate

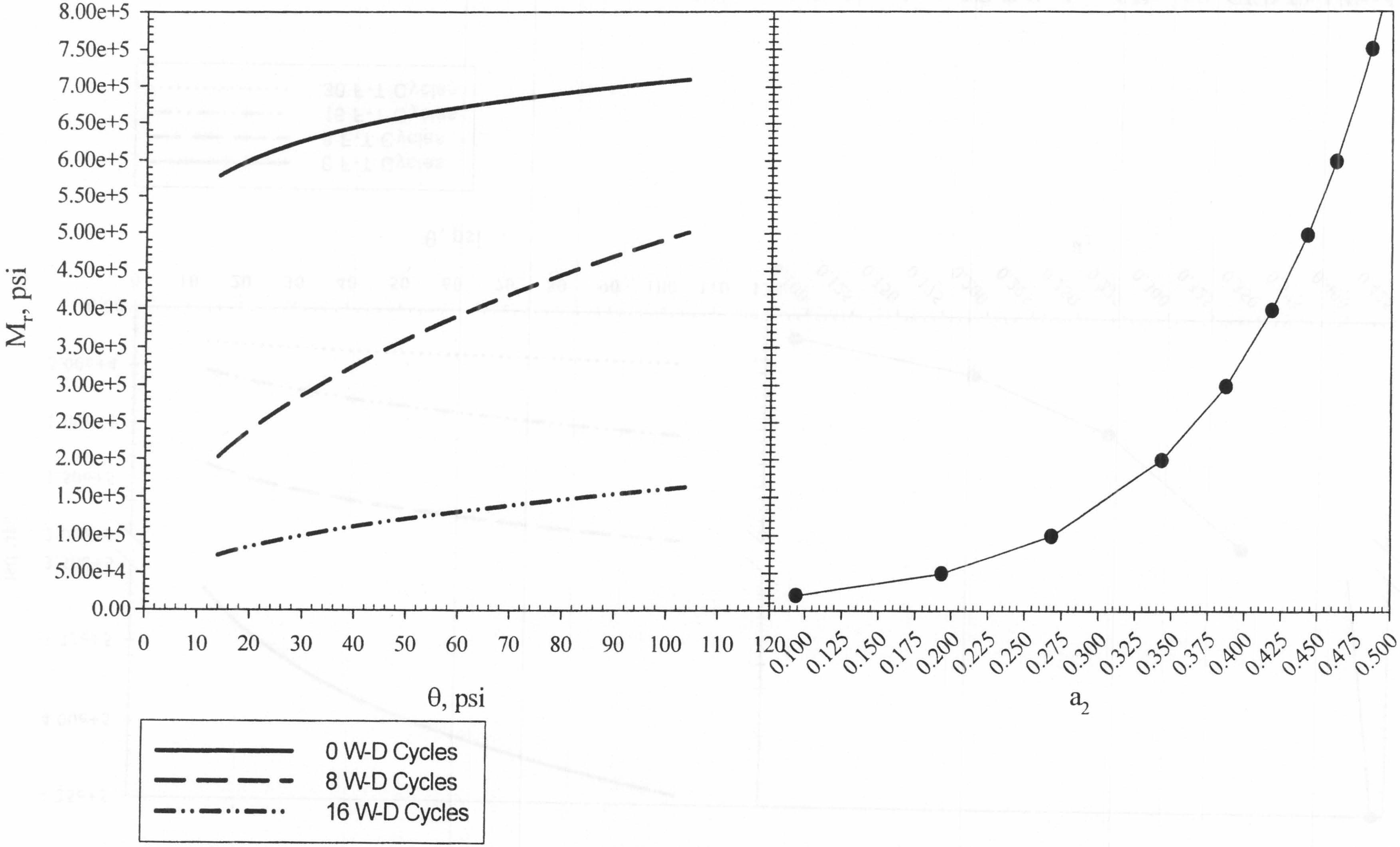


Figure 7-20 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Sawyer FBA-Stabilized Aggregate

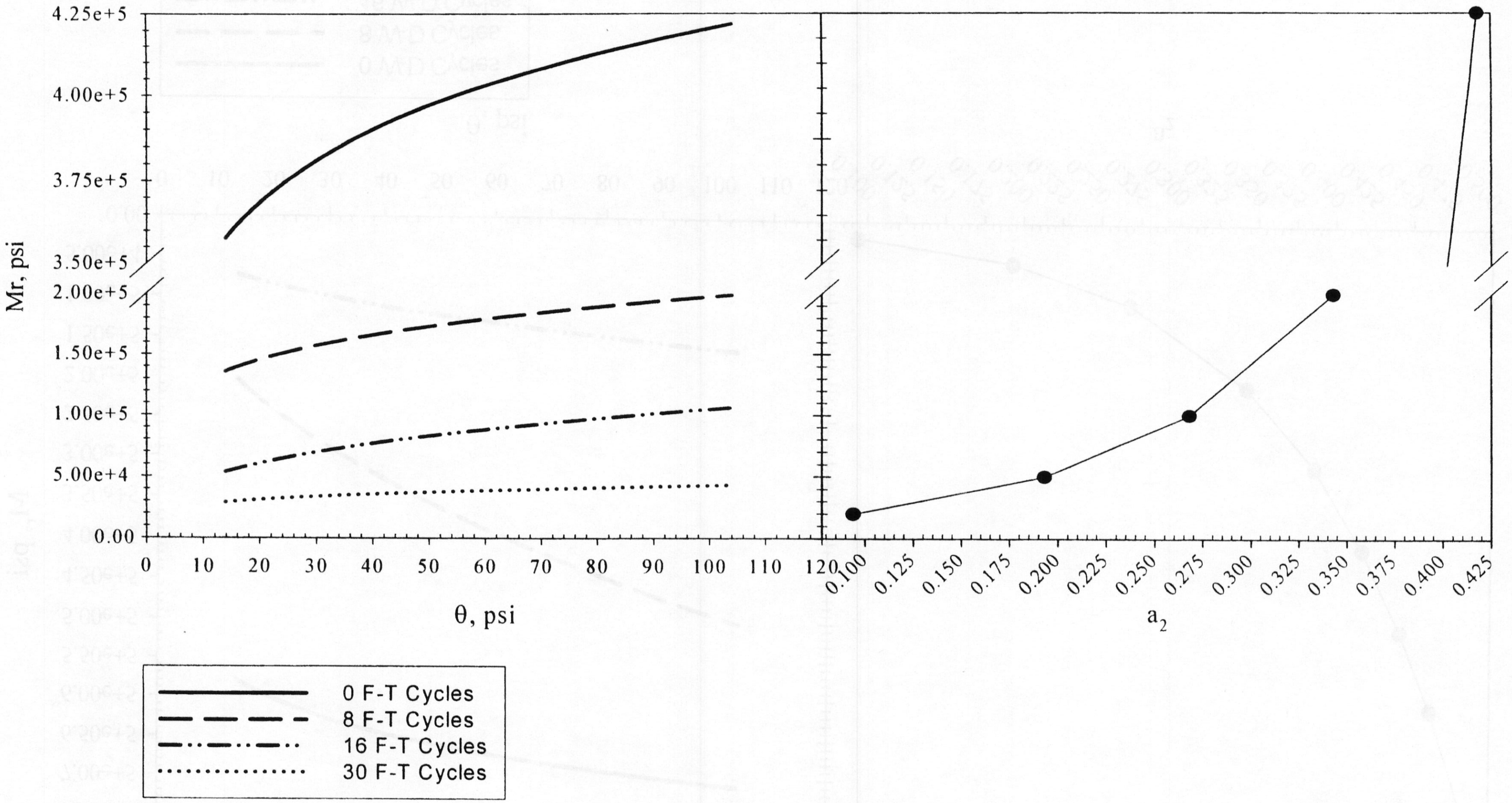


Figure 7-21 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Hanson CKD-Stabilized Aggregate

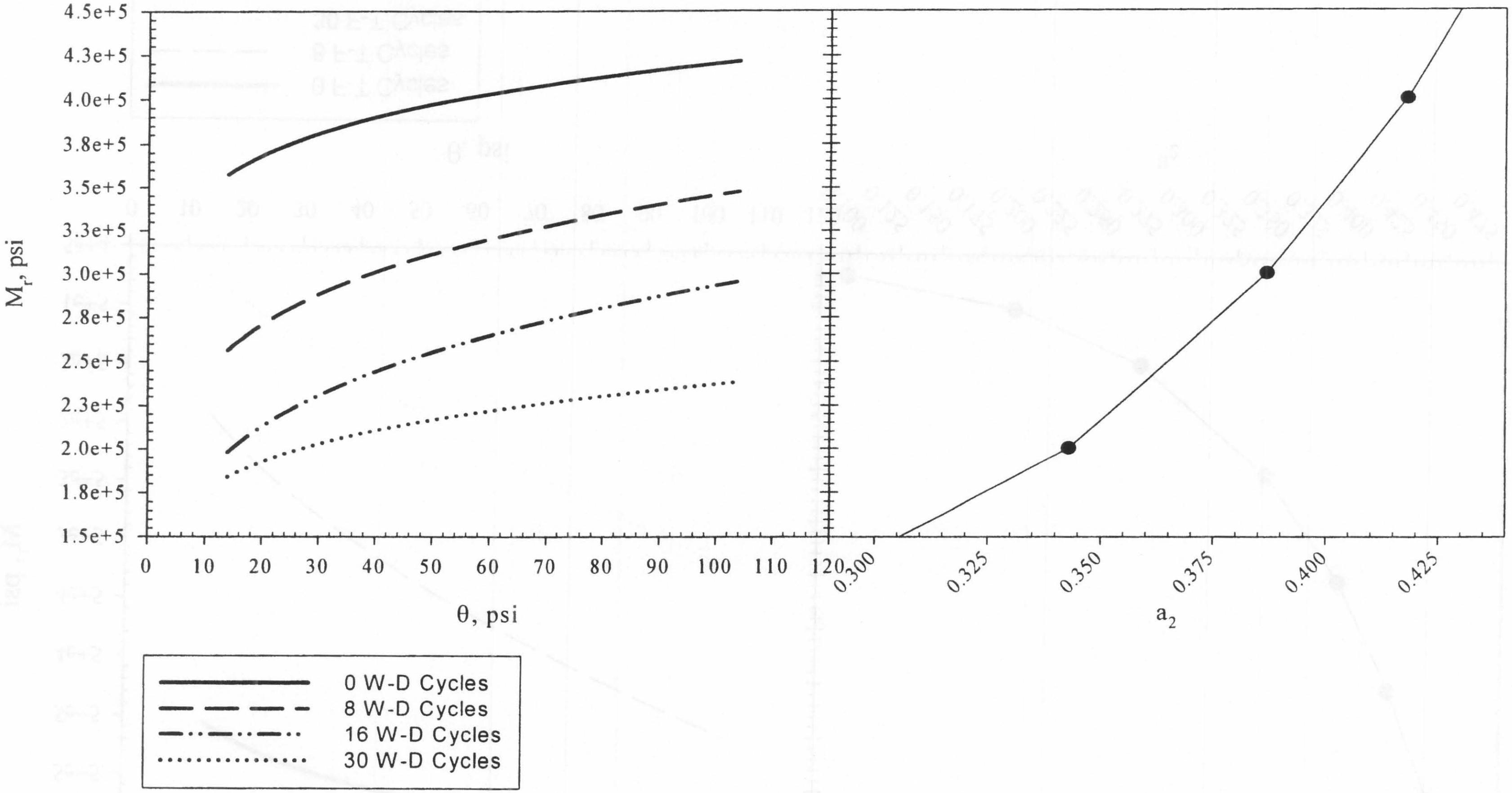


Figure 7-22 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Hanson CKD-Stabilized Aggregate

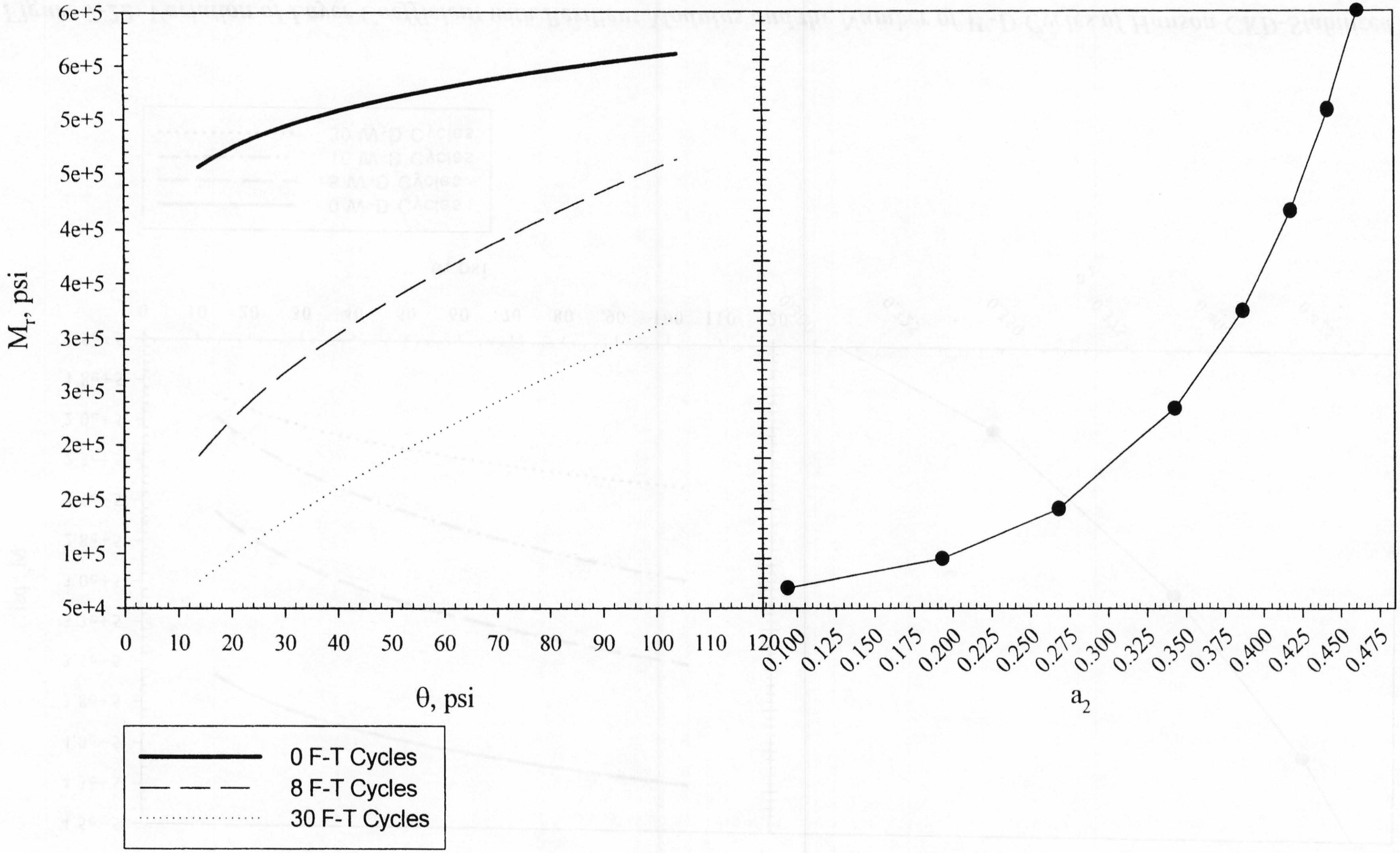


Figure 7-23 Variation of Layer Coefficient with Resilient Modulus and the Number of F-T Cycles of Hanson FBA-Stabilized Aggregate

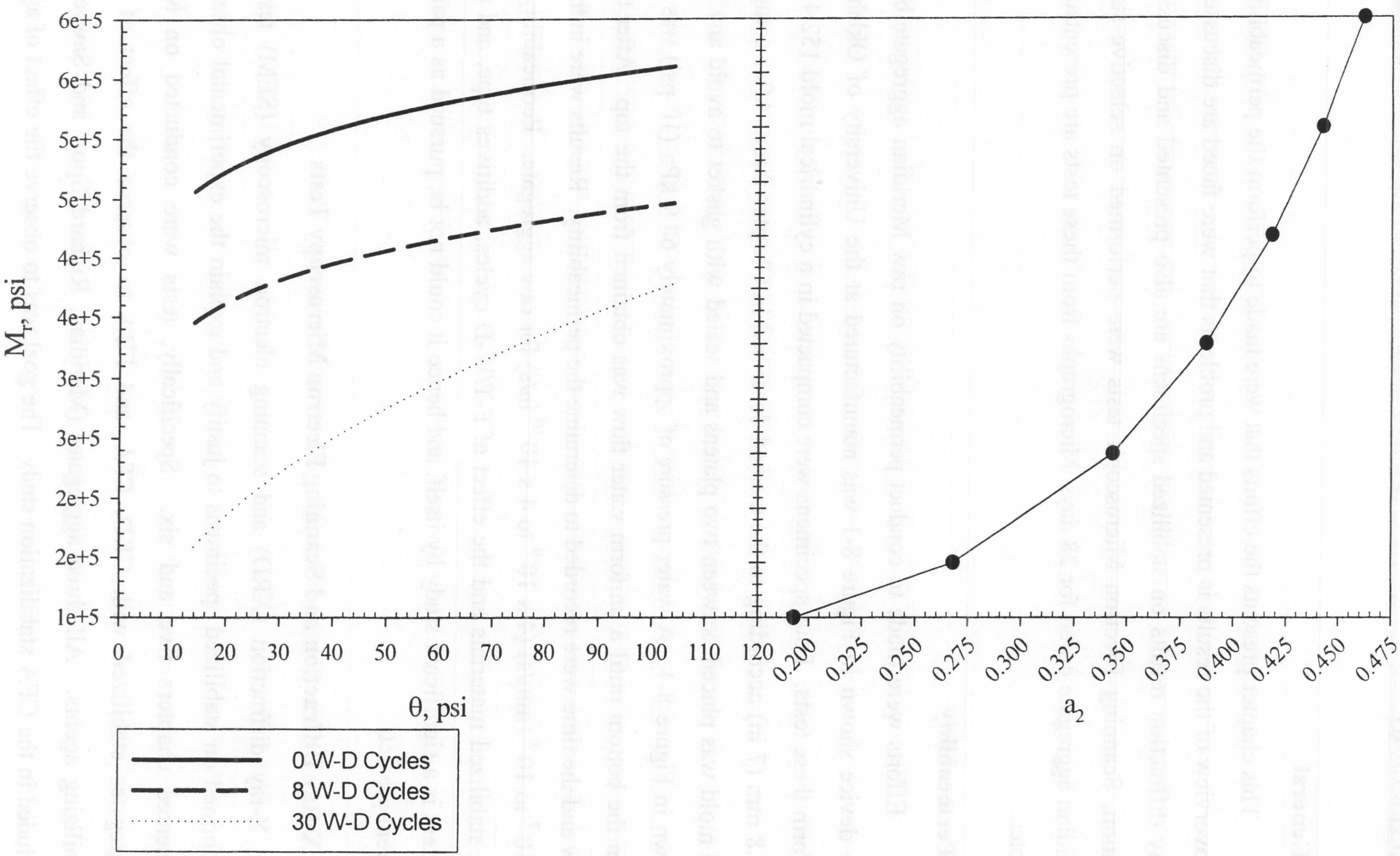


Figure 7-24 Variation of Layer Coefficient with Resilient Modulus and the Number of W-D Cycles of Hanson FBA-Stabilized Aggregate

8.1 General

This chapter presents the efforts that were made to perform the permeability tests. An overview of the results is presented and problems that were faced are discussed. The X-ray diffraction results on stabilized specimens are also presented and discussed. In addition, Scanning Electron Microscopic tests were performed on selective stabilized Meridian aggregate cured for 28 days. Micrographs from these tests are presented in this chapter.

8.2 Permeability

Efforts were made to conduct permeability on raw Meridian aggregate base. A new device shown in Figure 8-1 was manufactured at the University of Oklahoma to perform these tests. Four specimens were compacted in a cylindrical mold 152.4 mm by 177.8 mm (7 in) according to the method described in Chapter three. After compaction, The mold was placed between two platens and sealed with gasket to avoid any leak, as shown in Figure 8-1. A water pressure of approximately 68.9 kPa (10 psi) was applied from the bottom until a uniform water flow was obtained from the top. After that, the flow and the time were recorded to determine the permeability. Results were in the range of 10^{-7} to 10^{-8} (mm/s) (4 x 10^{-9} to 4 x 10^{-10} in/s) for raw aggregate. Permeability of raw and stabilized materials and the effect of F-T/W-D cycles, additives type, and additive content is a significant study by itself, and hence it could not be pursued as a part of the current project.

8.3 X-Ray Diffraction and Scanning Electron Microscopy Tests

The X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests were performed on stabilized specimens to justify and explain the experimental observations presented chapters five and six. Specifically, tests were conducted on Meridian aggregates stabilized with CKD, CFA, and FBA to observe the effect of various stabilizing agents. All three aggregates (Meridian, Richard Spur, and Sawyer) were included in the CFA stabilization study. The goal was to observe the effect of aggregate mineralogy on the Mr values. The diffractograms of the stabilized specimens are presented in Figures 8-2 and 8-3.

The Reference Intensity Ratio (RIR) method was used to analyze the data, rather than the intensity of the peak channel alone. The RIR is a constant relating the X-ray scattering power of a phase to that of the internal standard. The RIR method consists of fitting the raw data to a specific profile shape, eliminating the contribution of overlapping peaks, and subtracting background. This method is a quantitative method that calculates the weight % in the least-square fit of the identified minerals and compounds. However, the results are only as good as the RIR values can be, and profile error due to intensity (%) and positional mismatches in individual powder diffraction file (PDF) lines further jeopardize the accuracy of the final numbers.

The Jade 3.1 software was used and a summary of the calculated weight (%) is given in Tables 8-1 and 8-2. From the results in Tables 8-1 and 8-2, one can observe the following characteristic trends for the tested specimens:

1) Quartz (SiO_2) and calcite ($CaCO_3$) are the predominant minerals in the mixes. The aggregates (limestone and sandstone) and partly the stabilizing agents are the main sources of quartz and calcite.
2) Ettringite was found in all specimens, expect in the CFA-stabilized Sawyer aggregate. Ettringite of calcium aluminum sulfate hydrates (CASH) mineral type, and responsible for the early strength gain.
3) Also, gismondine was detected in all specimens, expect in the CKD-stabilized Meridian and CFA-stabilized Sawyer specimens. It is believed that gismondine is responsible for long-term performance of the stabilized specimens.
4) Hibonite, a calcium aluminum product, was detected only in the CFA-stabilized Sawyer specimens.
5) A trace of (C_3AH_6) ($3CaO.Al_2O_3.6H_2O$) was evident in all the specimens, except those of the CKD-stabilized Meridian aggregate.
6) Microcline was found in relatively large amounts in CFA-stabilized Richard Spur and FBA-stabilized Meridian specimens. A low amount of microcline was observed in CFA- and FBA-stabilized Meridian specimens.
7) Straetlingite ($2CaO.SiO_2.Al_2O_3.8H_2O$) was detected in all the mixtures.

8) Tobermorite was only found in CFA-stabilized Sawyer specimens.

From Tables 8-1 and 8-2, the mass percent (wt.%) of the cementing/mineral compounds is found to vary with the stabilizing agent and aggregate types. Unfortunately, no specific trends for each of the cementing compound with the resilient modulus were evident. The mass weight of ettringite in FBA-stabilized specimens is 2.6% lower than the corresponding value (3.3%) for the CKD-stabilized specimens, although the Mr values of the FBA-stabilized Meridian specimens are higher than those of the CKD specimens. To explore the trend issue further, it was decided to correlate the resilient modulus with the sum of the cementing compounds (SCC) (i.e., ettringite, gismondine, C3AH6, straetlingite, and tobermorite). Figure 8-4 shows the variation of Mr values with SCC. It is clear that Mr values increased approximately linearly with SCC, with a relatively high R^2 value (0.85). Such a correlation would be extremely helpful in better understanding and rationalizing the mechanisms associated with stabilization. It would also be helpful in evaluating the durability of stabilized aggregate bases, which is beyond the scope of this study.

The SEM tests were only performed on stabilized-Meridian specimens to observe the micro-structural changes in the matrix of CKD-, CFA-, and FBA-stabilized specimens and to visually examine the resulting hydration products. The SEM micrographs presented in Figure 8-5 show the evidence of crystal formation in the matrix aggregates. It is evident that the degree of crystal formation and paste surrounding the particles varies with stabilizing agents. For example, the micrographs show that CKD-stabilized specimens exhibit a lower intensity than CFA-stabilized specimens, followed by FBA-stabilized specimens. These experimental observations are consistent with the XRD trends.

Table 8-1 RIR Results of Meridian Aggregate Stabilized with CKD, CFA, and FBA.

Minerals/Specimen ID	Mass percent, Wt. (%)		
	10% CFA		
	Meridian	Richard Spur	Sawyer
Anhydrite	0	1.6	0
Calcite	85.9	70.4	0
Ettringite	2.6	2.6	0
Gismondine	4.7	8.9	7.3
Gypsum, $CaSO_4.2H_2O$	0	1.5	0
Hibonite	0	0	7.6
C3AH6	0.8	0.8	0.9
Microcline, $KAlSi_3O_8$	0	10.8	0
Periclase, MgO	0	0.7	0
Portlandite, $Ca(OH)_2$	0	0	0
Quartz, SiO_2	1.2	0.9	87
Straetlingite,	2.1	1.8	2.4
Tobermorite	0	0	2.1

Table 8-2 RIR Results of Meridian, Richard Spur, and Sawyer Aggregate Stabilized with CFA

Minerals/Specimen ID	Mass percent, Wt. (%)		
	10% CFA		
	Meridian	Richard Spur	Sawyer
Anhydrite	0	1.6	0
Calcite	85.9	70.4	0
Ettringite	2.6	2.6	0
Gismondine	4.7	8.9	7.3
Gypsum, $CaSO_4.2H_2O$	0	1.5	0
Hibonite	0	0	7.6
C_3AH_6	0.8	0.8	0.9
Microcline, $KAlSi_3O_8$	0	10.8	0
Periclase, MgO	0	0.7	0
Portlandite, Ca $(OH)_2$	0	0	0
Quartz, SiO_2	1.2	0.9	87
Straetlingite,	2.1	1.8	2.4
Tobermorite	0	0	2.1

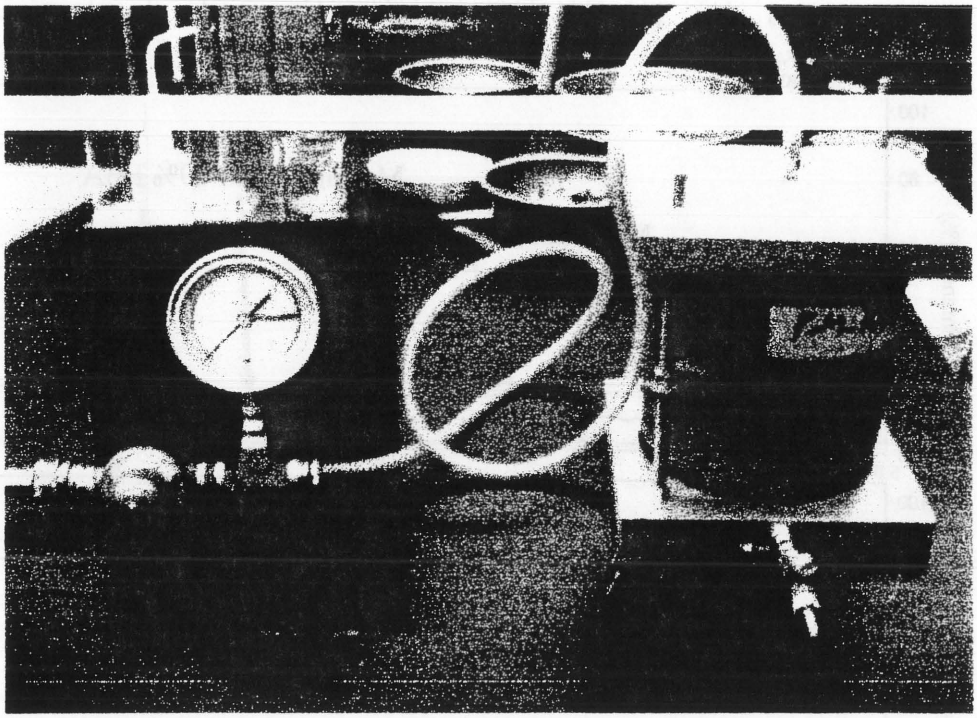


Figure 8-1 Photographic View of Permeability Device Used in This Study

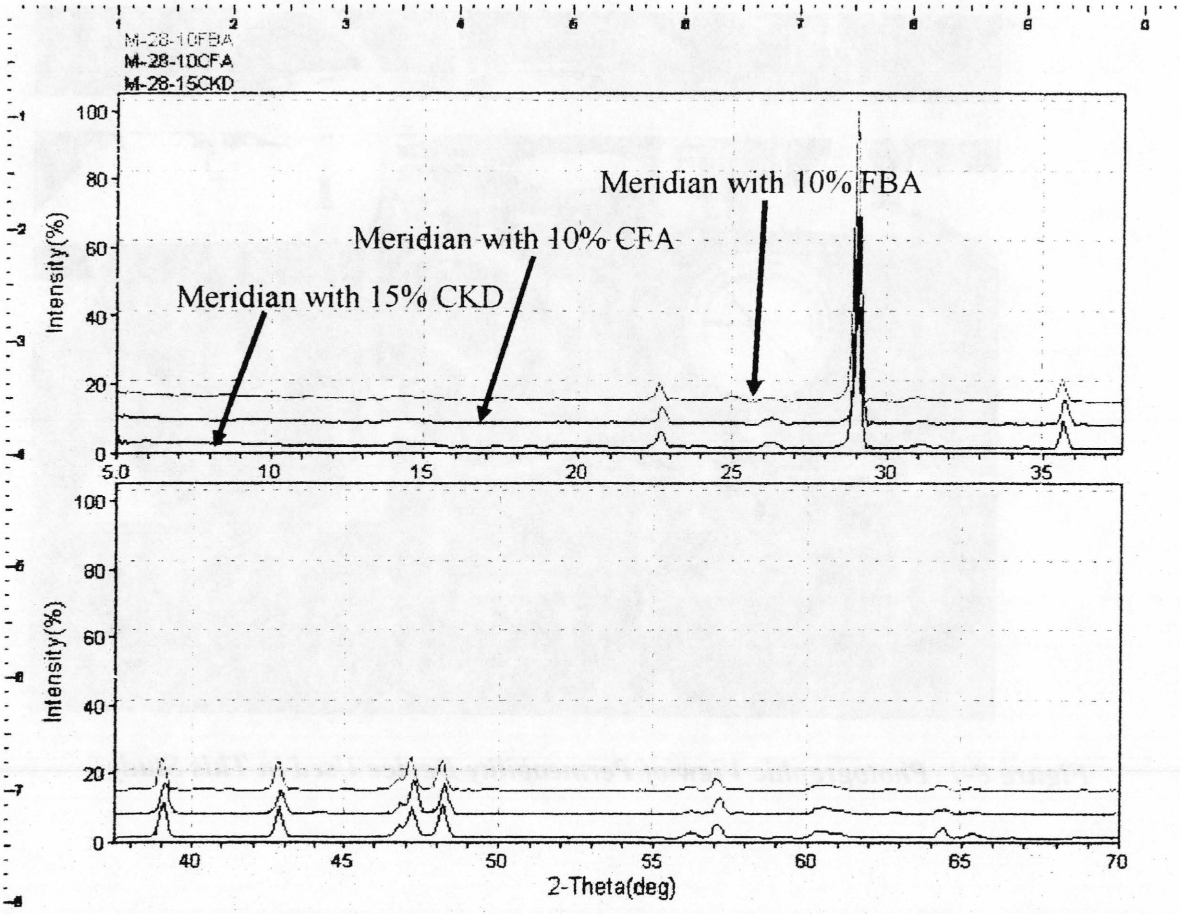


Figure 8-2 X-ray patterns for Meridian aggregate stabilized with CKD, CFA, and FBA.

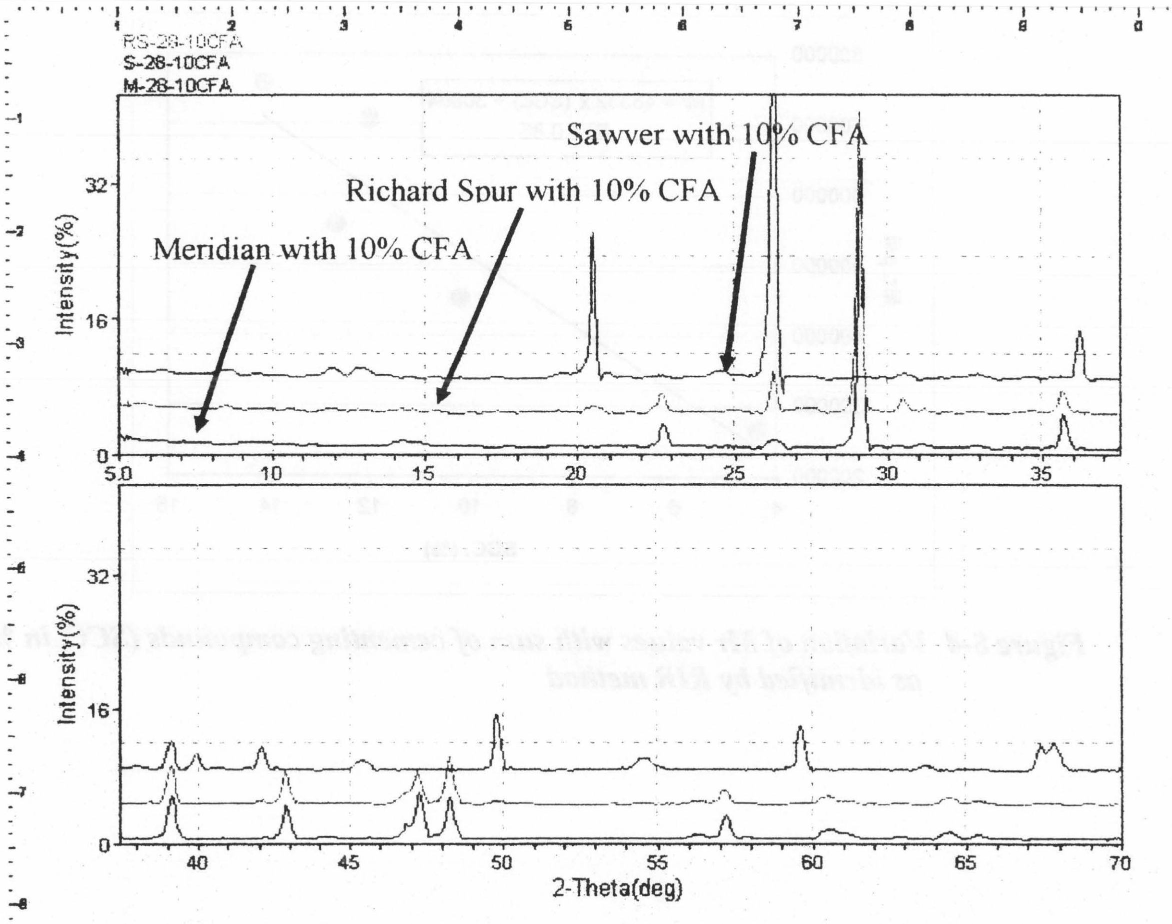


Figure 8-3 X-ray patterns for Meridian, Richard Spur, and Sawyer Stabilized with 10% CFA.

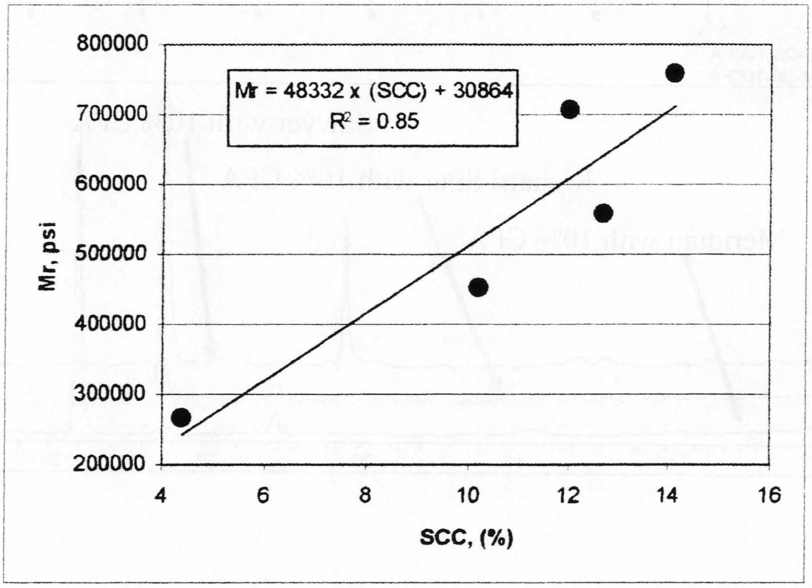


Figure 8-4 Variation of Mr values with sum of cementing compounds (SCC, in %) as identified by RIR method

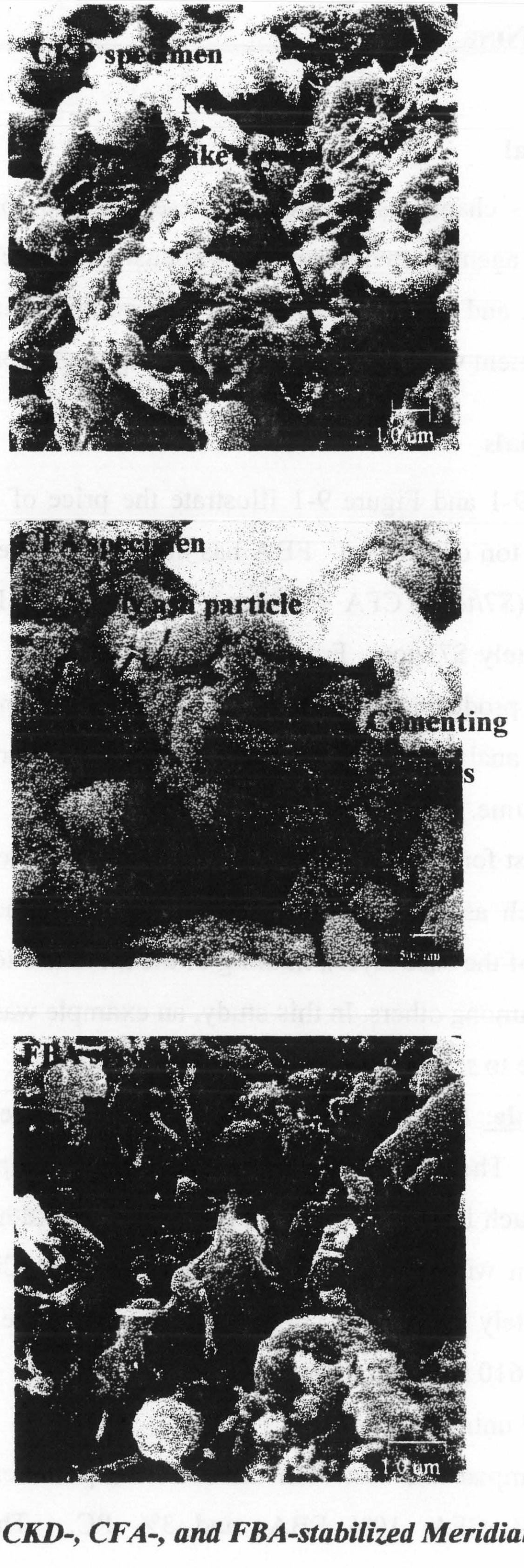


Figure 8-5 Micrographs of CKD-, CFA-, and FBA-stabilized Meridian specimens.

9.1 General

This chapter is devoted to presenting the cost of Meridian aggregate base and stabilizing agent, namely, cement kiln dust (CKD), class C fly ash (CFA), fluidized bed ash (FBA), and Portland cement (PC). A comparison between the cost of base materials for a pavement with untreated and treated aggregate base is presented.

9.2 Materials

Table 9-1 and Figure 9-1 illustrate the price of Meridian aggregate and stabilizing agents per ton of material. FBA has the lowest price of approximately $6/ton, followed by CKD ($7/ton), CFA ($19/ton), and then by PC that has the highest price of approximately $71/ton. From information provided by the producers of raw materials, the cost of producing Meridian aggregate is approximately $5/ton. These values are used in the cost analysis. It is important to note that the prices provided by manufacturers can vary with time.

The cost for constructing a base layer, un-stabilized or stabilized, depends upon many factors such as cost of production of aggregate and stabilizing agents (related to the thickness of the base layer), hauling of the materials to the project site, and compaction of the layer, among others. In this study, an example was used to illustrate how the cost will change due to stabilization with different additives.

Example: (1) Determine the cost of base materials for a two-lane highway with shoulders. The width of the pavement section is approximately 20.75 m (48 ft). The width of each lane is 3.66 m (12 ft), while the width of the shoulder is 3.048 m (10 ft). The section will be constructed in the Oklahoma City area, having an ESAL value of approximately 2,000,000. For comparison purpose, two different section lengths are used: (1) 1610 m (1 mile); and (2) 8050 m (5 miles). Meridian aggregate is used for both treated and untreated bases.

(2) Compare the cost with the cost of a pavement with a base stabilized with 15% CKD, 10% CFA, 10% FBA, and 3% PC. The thickness of the AC layer is

approximately, 9228.6 mm (9 in) and the subgrade modulus is approximately 34.45 MPa (5,000 psi).

Cost Evaluation for the One-Mile Section

A typical modulus for an untreated base is approximately 138 MPa (20,000 psi). This value will be used to determine the thickness of the base layer so that ESAL is approximately 2,000,000. From Table 6.4 in Chapter six, the thickness of the untreated base is approximately 304.8 mm (12 in). A total of 17,750 tons of raw Meridian aggregate is needed to provide this thickness for the section of the roadway considered in this example. Given the price of raw aggregate per ton, $5/ton, the total cost of the materials is approximately $88,704; excluding the hauling and the compaction price.

As for the FBA stabilized base, a modulus of approximately 4,823 MPa (700 ksi) could be considered typical. From Table 6.4, a 101.6 mm (4 in) stabilized aggregate base could produce an ESAL value of approximately 7,900,000, which is four times than the corresponding value of a pavement with untreated base. For all practical purposes, a 101.6 mm (4 in) thick base will be used to calculate the total cost. Thus, a total of 5, 376 tons of raw materials are needed, and approximately 538 tons of FBA is needed for the aforementioned section. The total cost of the raw Meridian aggregate and FBA is approximately $30,106 (considering the cost of raw Meridian to be $26,880, and the cost of FBA to be $3,228). As for CKD, a modulus of 1,722 MPa (250 ksi) is used, and thus the thickness of the stabilized layer should be approximately 127 mm (5in) (refer to Table 6.4). For this thickness, the amount of raw aggregate needed is approximately 9,100 tons and the weight of CKD needed is approximately 964 tons. The total price of these materials is $38,888 of which $32,140 for the aggregate and $6,748 for the CKD. The modulus of a stabilized aggregate base with CFA is considered approximately 2,756 MPa (400 ksi), and the thickness, from Table 6.4, is approximately 101.6 mm (4 in), although it produces a higher ESAL (3, 048,800) than the required ESAL. As a result, a total of 5,376 tons of raw materials and approximately 538 tons of CFA will be needed to construct the section. The cost for such a layer is approximately $37,094 ($26,880 for Meridian aggregate, and $10,222 for CFA). A thickness of 101.6 mm (4 in) is required for a base stabilized with Portland cement. The amount of raw aggregate needed is approximately 5,741 tons that will cost approximately $28,705. The corresponding weight of PC is approximately 172 tons that will cost approximately $12,141. Thus, the total cost is approximately $40,936.

According to Sewell Brother Company, Oklahoma, the cost for compacting a square yard of raw aggregate base is approximately 30 cents, while the price increases for an aggregate base mixed with additives (approximately $1.50 per square yard). The latter cost does not change with the type of additives, as indicated by the company. For the aforementioned section, the total cost to compact an aggregate base without additives is approximately $8,448, and the cost for an aggregate base with additives is approximately $42,240, regardless of the type of additives.

As for hauling, the price to haul Meridian aggregate (Willis Quarry, now called Martin Marietta) to a project site in the Oklahoma City area is approximately $7 per ton. For the aforementioned section, the hauling cost for aggregate (17,741 tons) will be approximately $124,186. According to Lafarge Company, the hauling cost of CKD (Tulsa plant, Oklahoma) to a hypothetical project site in the Oklahoma City area is approximately $18 per ton. For the section having a CKD-stabilized aggregate base, the cost for hauling the materials will be approximately $62,350 of which $44,996 for Meridian aggregate and $17,352 for CKD. The equivalent cost for the CFA section will be approximately $47,309 ($37,632 for Meridian aggregate (Willis Quarry), and $9,677 for CFA (Oklaunion plant, Texas), assuming the hauling cost for CFA to be $18 per ton. The equivalent hauling cost for the FBA section will be $50,534, assuming a rate of $24 per ton. The freight cost for the PC section will be $41,740 of which $40,187 for hauling of Meridian aggregate ($7 per ton), and $1,553 for hauling of PC ($ 9 per ton), according to Dolese Bros, Co. in Oklahoma City.

From the aforementioned results, it is obvious that the cost of materials for a base layer without stabilization is most expensive, approximately $125,000. From Figure 9-2, one can see that chemical stabilization with CKD, CFA, FBA, and PC reduces the materials' cost significantly because stabilization reduces the thickness of the base layer, and thus the bulk materials. The cost of materials is reduced to approximately $30,000 for the FBA section, $37,000 for the CFA section, $39,000 for the CKD section, and $41,000 for the PC section. Same trend was observed for the cost of hauling the materials to the project, where the hauling cost for the un-stabilized section is higher than that for the stabilized section. It is also important to note that the hauling cost is higher than the materials' cost because of the project location. For example, the hauling cost for the un-stabilized section is approximately $125,000 compared to $88,700 for the materials' cost. Compaction costs for section with stabilization are significantly higher than the compaction cost for raw aggregate, and it does not vary with the type of stabilizing agents. One can also see from Figure 9-2 that the cost for constructing the FBA section in the Oklahoma City area is slightly cheaper than constructing the same section with CFA, followed by CKD, and PC.

Cost Evaluation for the Five-Mile Section

A summary of the cost analysis for the 8,050 m (five-mile) section is illustrated in Figure 9-3. A trend similar to that for the one-mile section is observed, the FBA section being the lowest compared to CFA, CKD, PC, and the section without stabilization. The cost of the FBA section is approximately 45% cheaper than the section without stabilization. It is also evident that the differences among FBA, CFA, and PC sections are relatively small ranging between $10,000 and $20,000.

The location of the project is an important factor in the above analysis and it can affect the total cost because the hauling cost varies with location. The cost may also change with the aggregate type. The aforementioned example is provided just as an illustration; no attempts were made to compare the cost for different sections constructed with different types of aggregates such as Richard Spur, Sawyer, and Hanson.

Table 9-1 Cost of Stabilizing Agents

Additive type	Agrgegate Type	OAC (%)	Weight of Add. / 1 Ton of Aggregate	Cost ($/ton)	Total ($)
CKD	Meridian	15	0.15	7	1.05
CFA	Meridian	10	0.1	19	1.9
FBA	Meridian	10	0.1	6	0.6
PC	Meridian	3	0.03	71	2.13
CKD	Richard Spur	15	0.15	7	1.05
CFA	Richard Spur	10	0.1	19	1.9
FBA	Richard Spur	10	0.1	6	0.6
CKD	Sawyer	15	0.15	7	1.05
CFA	Sawyer	10	0.1	19	1.9
FBA	Sawyer	10	0.1	6	0.6
CKD	Hanson	15	0.15	7	1.05
FBA	Hanson	10	0.1	6	0.6
OAC, Optimum Additive Content					
Prices herein are subjeced to changes, and represent the price at a specific period of time					

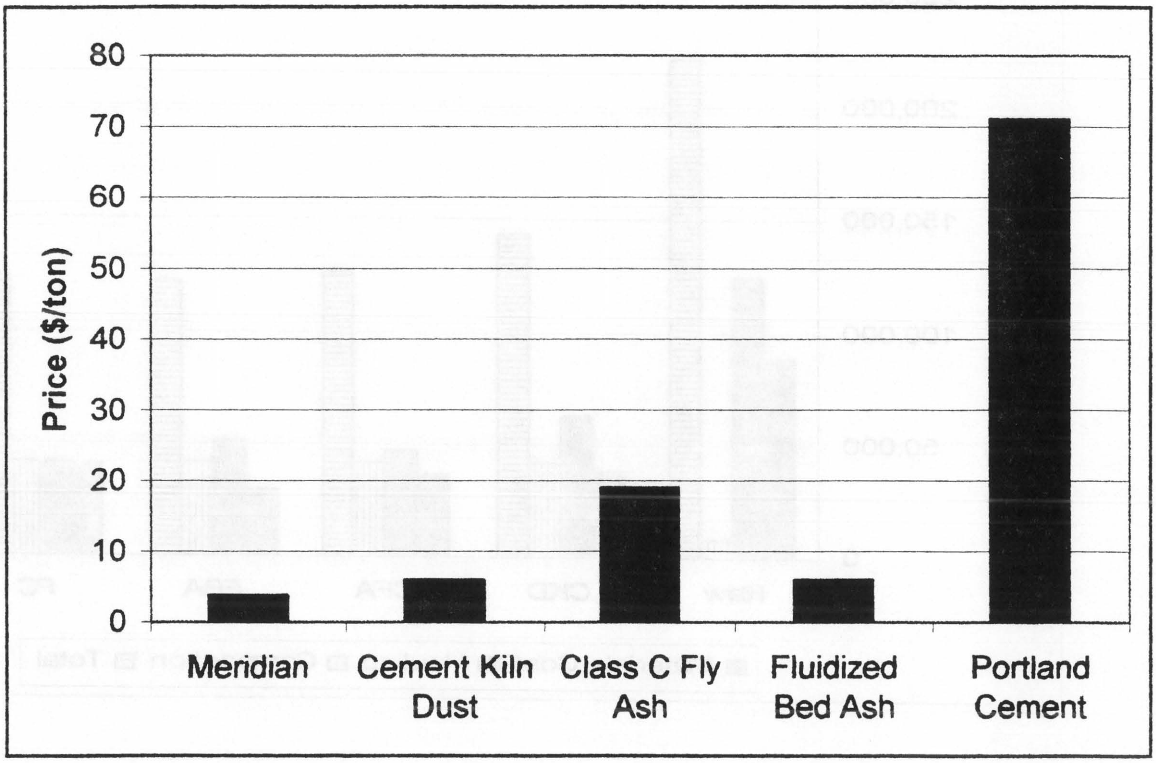


Figure 9-1 Cost of Stabilizing Agents and Meridian Aggregate

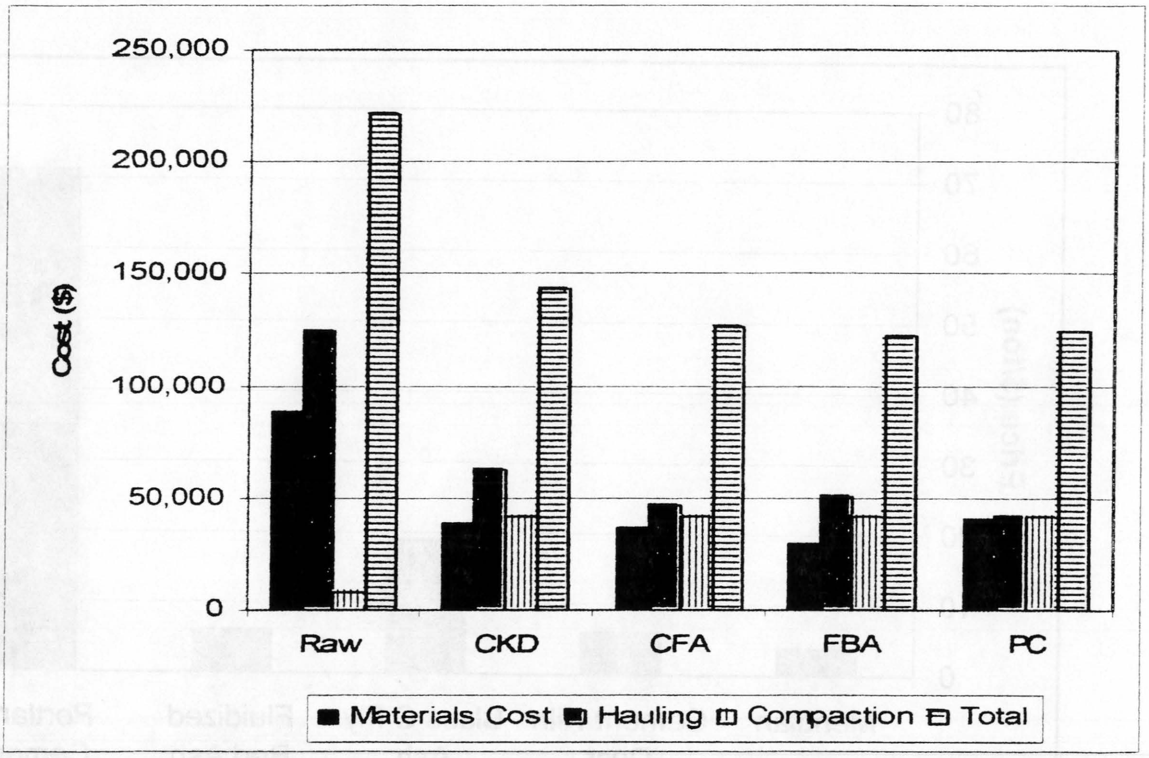


Figure 9-2 Cost for Constructing an Aggregate Base Layer with and without Stabilization in the Oklahoma City Area for One-Mile Section

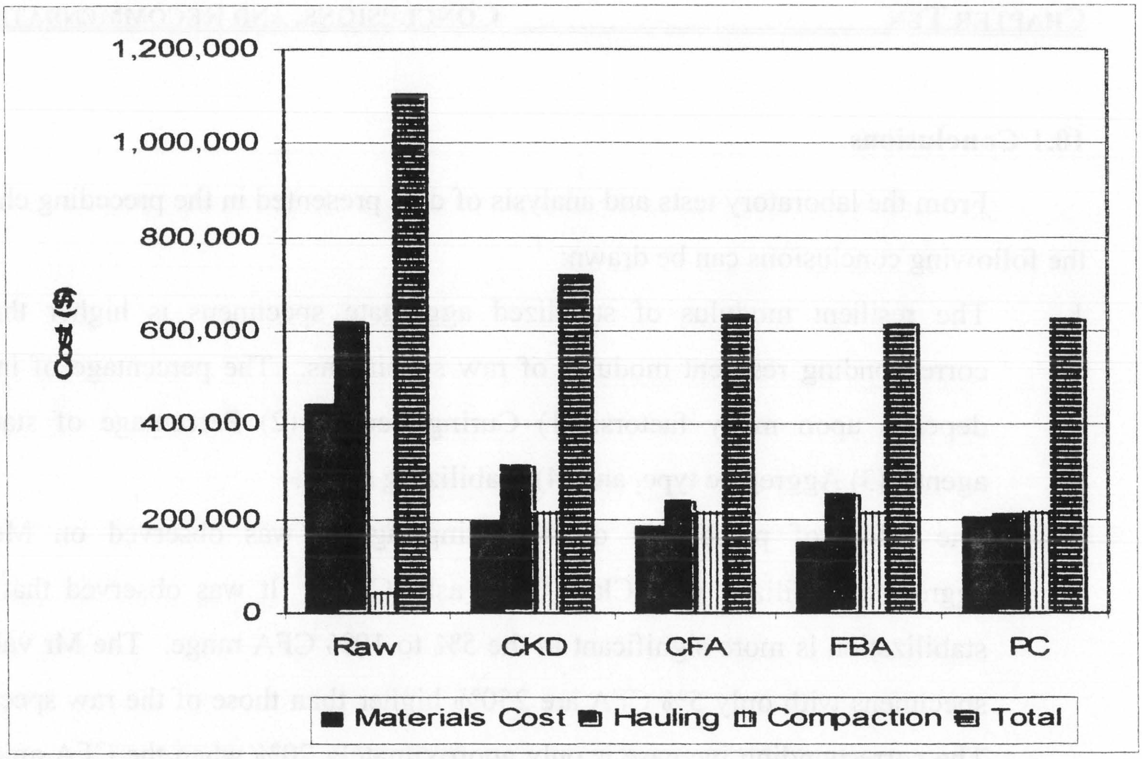


Figure 9-3 Cost for Constructing an Aggregate Base Layer with and without Stabilization in the Oklahoma City Area for Five-Mile Section

10.1 Conclusions

From the laboratory tests and analysis of data presented in the preceding chapters, the following conclusions can be drawn:

1. The resilient modulus of stabilized aggregate specimens is higher than the corresponding resilient modulus of raw specimens. The percentage of increase depends upon many factors: (1) Curing period, (2) Percentage of stabilized agents, (3) Aggregate type, and (4) Stabilizing agent.
2. The effect of percentage of stabilizing agents was observed on Meridian aggregate stabilized with Class C fly ash (CFA). It was observed that CFA-stabilization is more significant in the 5% to 10% CFA range. The Mr values of specimens with only 5% CFA are 250% higher than those of the raw specimens. The corresponding increase is only approximately 20% when the CFA amount is increased from 10% to 15%. Considering strength gain and field application scenarios, 10% CFA is considered to be the optimum additive content.
3. Curing period is a sensitive parameter. The Mr values of CFA-stabilized aggregate increase with increasing curing period. The Mr values of 3-day cured samples are approximately 280% higher than the corresponding Mr values of raw specimens. The 28-day cured samples have Mr values as much as 40% higher than the 3-day cured samples. The Mr values of 90-day cured samples, on the other hand, were only approximately 25% higher than the Mr values of 28-day cured samples. Thus, 28-day curing can be used in the field.
4. The Mr values of PC-stabilized specimens are higher than the corresponding Mr values of FBA-stabilized specimens, followed by CFA, and then by CKD. The increase is due to the chemical properties of the additives.
5. The aggregate mineralogy is an important factor in stabilizing aggregate base. Results show that different aggregate mineralogy could produce different Mr values even when stabilized with the same stabilizing agents. For examples, CKD-stabilized Meridian aggregate (Limestone) had Mr values lower than

Sawyer, a sandstone aggregate.

6. F-T and W-D cycles have deleterious effect on stabilized samples, the effect of W-D actions being more dominant. This fact is true when membranes around the specimens were not removed during the F-T cycles (Phase I). In Phase (II), on the other hand, F-T cycles produced much severity to the stabilized specimens than W-D cycles. As a result, the degree of severity depends upon the procedure itself.

7. Two different phenomena are involved when stabilized samples are subjected to F-T or W-D cycles. The first one is the positive effect of curing time, the second is the negative effect of F-T or W-D action.

8. The unconfined compressive strength (UCS) and modulus elasticity (E) values increase with increasing F-T/W-D cycles up to 30 cycles. Samples stabilized with 10% CFA and subjected to 30 cycles have average UCS and E values higher than those subjected to 0, 4, and 12 cycles. The UCS of 3-day cured samples subjected to 4, 12, and 30 W-D cycles were approximately 63%, 130%, and 130%, respectively, higher than the corresponding values for samples without any W-D cycles.

9. The tensile strain at the bottom of an asphalt concrete layer, the compressive strain at the top of subgrade and the allowable repetition are significantly higher when the aggregate base is stabilized. F-T/W-D cycles have an effect on these parameters. A positive effect of F-T cycles on resilient modulus produces an increase in ESAL and vice versa.

10. The layer coefficients of the stabilized specimens are higher than the corresponding values of raw aggregate.

11. The SEM analysis shows formation of crystals with aggregate matrix as a result of stabilization. It is reasoned that the crystals within the matrix provide better interlocking between the particles and possible higher resistance to shear deformation and also reduce void within the matrix resulting in overall strength gain. The results of the analysis conform to the results of the Mr and UCS tests.

12. The XRD analyses show chemical activity within the aggregate matrix as a result of stabilization. It is evident that the hydration of ash was followed by crystal

formation within the matrix observed by the micrographs, as seen in the SEM analyses.

10.2 Recommendations

The following recommendations are made for further studies:

1. Resilient modulus test methods are only available for unbound/untreated base/subbase, subgrade soil and aggregate. There is no common test method available today that is acceptable to all the transportation agencies in the country. It is important to establish new test methods for treated/stabilized aggregate base/subbase and subgrade. This is particularly important since resilient modulus is a pertinent parameter in pavement design, as recommended by AASHTO.
2. No systematic study has been conducted yet on Mr values of aggregate with the measurement of pore water pressure. As such, the impact of pore water pressure on Mr values is not known. It is recommended that research be conducted with the measurement of pore water pressure.
3. From the literature review conducted, there is no standard test available to evaluate the effect of F-T/W-D cycles on the properties of stabilized aggregate base. It is important to conduct additional studies to develop standardized test procedures addressing the effects of F-T/W-D actions on aggregate base and other materials. Also, it is important to explore the combined effect of both F-T and W-D cycles on Mr values and other properties.
4. Permeability is an important material property in pavement design. This property has not received the desired attention. Further studies should be undertaken to investigate permeability of stabilized and unstabilized aggregate base. Also, it would be interesting to observe the effect of gradation on the permeability of a stabilized aggregate base.
5. Flexural strength influences the structural response and fatigue performance of a stabilized aggregate base. From the literature survey conducted, there is no standard test available to evaluate the flexural strength of a stabilized aggregate base. Therefore, it is recommended that studies be conducted focusing on the development of appropriate test procedures.

6. It was concluded that the severity of damage due to F-T/W-D cycles depends on the procedure itself. Thus, a standardize procedure is needed to evaluate the durability of stabilized aggregate. The procedure should simulate the field condition.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), (1999) "*Determining the Resilient Modulus of Soils and Aggregate Materials,*" AASHTO Part II Test Methods 1999, Designation T307-99, pp. 733-758.

American Association of State Highway and Transportation Officials (AASHTO), (1986) " *AASHTO Guide for Design of Pavement,* " Washington D.C., 1986.

Asphalt Institute (AI), (1982) *"Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1),"* 9th Edition, Research. Report 82-2.

Asphalt Institute (AI), (1991) *"Thickness Design-Asphalt Pavements for Highways and Streets,"* Manual Series, No.1, Asphalt Institute, 1991.

American Society of Testing and Materials (ASTM), (1998b) *"Unconfined Compressive strength of compacted Soil-Lime Mixtures,"* Annual Book of ASTM 1998, Designation D 5102-96, pp. 93-98.

Chen, D.H., (1994) "*Resilient Modulus of Aggregate Bases and a Mechanistic-Empirical Methodology for Flexible Pavement,"* Ph.D. Dissertation, University of Oklahoma, Norman,1994.

Claussen, A., Edwards, J.M., Sommer, P., and Uge, P., (1977) *"Asphalt Pavement Design-The Shell Method,"* Proceedings 4th International Conference on the Structural Design of Asphalt Pavement, Vol. 1, pp. 39-74.

Comeau, M.C., (2001) *"Conditions and Performance of the Interstate System—After 40 Years,"* <http://www.tfhrc.gov/pubrds/summer96/p96su40.htm> January, 2001.

Fanous, F., Coree, B., and Wood, D., (1999) *"Response of Iowa Pavements to Heavy Agricultural Loads,"* Interim Report, Iowa DOT Project TR-1075, 1999.

Huang, Y.H., (1993) *"Pavement Analysis and Design,"* Prentice Hall, Inc. Englewood liffs, New Jersey.

Kerkhoven, R.E., and Dormon, G.M., (1953) *"Some Considerations on the California Bearing Ratio Method for the Design of Flexible Pavement,"* Shell Bitumen Monograph No.1, 1953.

Khoury, N.N. (2001) "*The Effect of Freeze-Thaw and Wet-Dry Cycles on Resilient Modulus of Class C Fly Ash Stabilized Aggregate Base,*" The University of Oklahoma, Master Thesis, 2001.

Little, D.N., E.H. Males, J.R. Pursinski, and B. Stewart. Cementitious Stabilization. http://www.nationalacademies.org/trb/publications/millennium/00016.pdf. Accessed Jan.

10, 2001.

National Cooperative Highway Research Report (NCHRP) (1992). *Calibrated Mechanistic Structural Analysis Procedures for Pavements.* Final Report, Project 1-26, May, 1992.

National Cooperative Highway Research Report (NCHRP), (1997) *"Laboratory Determination of Resilient Modulus for Flexible Pavement Design,"* Final Report, Project 1-28, June,1997.

NCHRP (2000), "Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design," Draft Document, prepared for National Cooperative Highway Research Program, Project 1-28A, Transportation Research Board, National Research Council, June, 2000.

Oklahoma Department of Transportation (ODOT), (1996) *" Standard Specifications for Highway Construction."*

Pandey, K. K., (1996) *" Evaluation of Resilient Modulus and Layer Coefficient of a Coal Ash Stabilized Marginal aggregate Base for AASHTO Flexible Pavement Design,"* Ph.D., Dissertation, University of Oklahoma, Norman, Oklahoma, 1996.

Roberts, F. L., Kandhal, P. S., Broum, R. E., Lee, D., and Kennedy, T. W., (1996) *"Hot Mix Asphalt Materials, Mixture Design, and Construction,"* 2nd Edition, Catalog Number, 91-60083, 1996.

Smith, R. E., Darter, M. I., and Herrin, S. M., (1979) *"Highway Pavement Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey,"* Contract DOT-FH-11-9175/NCHRP 1-19, Federal Highway Administration.

Thompson, M.R., (1987) *"ILLI-PAVE Based Full-Depth Asphalt Concrete Pavement Design Procedure,"* Proceedings, 6th International Conference on Structural Design of Asphalt, Vol.1, pp. 13-22.

Uzan, J., (1999) *"Permanent Deformation of a Granular Base Material,"* 78th Annual Meeting of TRB, January, 1999.

Van Til, C.J., McCullough, B.F., and Vallerga, B.A., (1972) *"Evaluation of AASHTO Interim Guides for Design of Pavement Structures,"* NCHRP Report 128, 1972.

Yi L., (1995) *"Resilient moduli of fly ash stabilized aggregates."* Master's thesis, University of Oklahoma, Norman, 1995.

Zaman M., Laguros J., Tian P., Zhu J., Pandey K., (1998) *" Resilient Moduli of Raw and Stabilized Aggregate Bases and evaluations of Layer Coefficients for AASHTO Flexible*

Pavement Design," Final report, Submitted to ODOT, Item 2199, ORA 125-4262, August 1998.

Zhu, J., (1998) " *Characterization of Cement-Kiln-Dust Stabilized Base/Subbase Aggregate*," Ph.D. Dissertation, University of Oklahoma, Norman, 1998.