ESTABLISH SUBGRADE SUPPORT VALUES FOR TYPICAL SOILS IN NEW ENGLAND

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16. Abstract

The main objective of this research project was to establish prediction models for subgrade support (resilient modulus, M_R) values for typical soils in New England. This soil strength property can be measured in the laboratory by means of repeated load triaxial tests. Non-destructive tests like Falling Weight Deflectometer (FWD) can be used to estimate the modulus value using backcalculation process. The current study used data extracted from Long Term Pavement Performance Information Management System (LTPP IMS) Database for 300 test specimens from 19 states in New England and nearby regions in the U.S. and 2 provinces in Canada. Prediction equations were developed using SAS® for six AASHTO soil types viz. A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6 and USCS soil types Coarse Grained Soils and Fine Grained Soils found in New England region to estimate resilient modulus. To verify the prediction models, M_R values for 5 types of soils in New England were determined from laboratory testing using AASHTO standards. The predicted and laboratory measured M_R values matched reasonably well for the soils considered. Also an attempt was made to obtain relationship between laboratory M_R values and FWD backcalculated modulus from the LTPP test data. No definitive conclusion could be drawn from the analysis. However, in general, FWD backcalculated modulus values were observed to be greater than the laboratory determined modulus values for the same soil type.

17. Key Words
Resilient Modulus, Subgrade, AASHTO soil types, Regression, Prediction Models, Falling Weight Deflectometer, Backcalculated modulus.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F

-40 0 40 80 120 180 200

-40 -20 0 20 40 60 80 100

°C 37 °C

ESTABLISH SUBGRADE SUPPORT VALUES FOR TYPICAL SOILS IN NEW ENGLAND

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EXECUTIVE SUMMARY

The main objective of this research project was to establish prediction models for subgrade support (resilient modulus, M_R) values for typical soils in New England. Resilient modulus is a definitive elastic material property of soil recognizing certain nonlinear characteristics and used to characterize roadbed soil for pavement design. This soil strength property can be measured in the laboratory by means of repeated load triaxial tests. Non-destructive tests like Falling Weight Deflectometer (FWD) can be used to estimate the modulus value using backcalculation process.

In order to identify the major soil types occurring in New England region, a thorough review of United States Department of Agriculture (USDA) soil survey reports was conducted. The predominant soil types identified for the five New England States are: Connecticut - A-2 and A-4; Maine - A-1, A-2, A-3, A-4, A-5, and A-6; Massachusetts - A-1, A-2, A-3, A-4, A-5, and A-6; New Hampshire – A-1, A-2, and A-4; Vermont - A-1, A-2, A-4, A-6, and A-7. The predominant soil type in Rhode Island could not be identified because the soil types occurring in the entire state has been given, county wise soil types is not available.

Resilient modulus prediction models were developed for six predominant AASHTO (American Association of State Highway and Transportation Officials) soil types (A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6) found in New England using SAS®. The current study used data extracted from Long Term Pavement Performance Information Management System (LTPP IMS) Database for 300 test specimens from 19 states in New England and nearby regions in the U.S. and 2 provinces in Canada. Soil types A-1-a, A-2-5, A-2-7, A-5, and A-7-5 were not present in the test sites considered for this study. Generalized constitutive model consisting bulk stress and octahedral shear stress was used to predict the resilient modulus of subgrade soils by developing regression equations for the k coefficients that relate them to the soil properties. Three set of prediction models were developed for each soil type. The first set of models were developed from all available soil samples for a particular soil type, the second set of models were developed from only those samples that had been compacted at optimum moisture content during

M_R test, and the third set of models were developed taking samples that had been compacted at insitu moisture content during M_R test. The regression equations show that for different k coefficients, different set of soil properties have the major contribution. The R^2 values obtained for the k coefficient prediction models varied from 0.30 to 0.99.

Furthermore, the data collected from the LTPP database were classified according to Unified Soil Classification System (USCS) into Coarse Grained and Fine Grained soils and separate prediction models were developed for each of them. Two models were developed for coarse grained soils, one with all coarse grained soil samples available in LTPP database and other with only those samples that had Uniformity Coefficient (CU) less than 100. In these cases, the R^2 values obtained for the k coefficient prediction models varied from 0.22 to 0.63.

The R^2 values obtained in the present study are not as high as those reported in some of the previous studies which were based on testing of a rather limited number of soil samples with controlled soil parameters and consistent laboratory environment. The soil specimens collected for tests in the LTPP program, whose results were used in this study, were from varied and wide locations. Moreover, the resilient modulus test results reported in the LTPP database were not obtained from a single laboratory so there is a possibility of error due to equipment/operator variability.

To verify the prediction models, M_R values for 5 types of soils in New England were determined from laboratory testing using AASHTO standards. The predicted and laboratory measured M_R values matched reasonably well when the soil properties values for the samples were within the range of the values used in developing the prediction models.

Also an attempt was made to obtain relationship between laboratory M_R values and FWD backcalculated modulus from the LTPP test data. No definitive conclusion could be drawn from the analysis due to lack of data of these two types of tests performed under similar conditions of moisture, density, and season and field stress data. However, in general, FWD backcalculated modulus values were observed to be greater than the laboratory determined modulus values for the same soil type.

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1. INTRODUCTION

Subgrade soil is an important part in both flexible and rigid pavement structures. To effectively and economically design pavement systems, subgrade response must be evaluated. The 1993 American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures and 2002 Design Guide-Design of New and Rehabilitated Pavement Structures have noted resilient modulus (M_R) value of subgrade soils as the primary property needed for pavement design and analysis.

Flexible pavement (Figure 1) design based on the resilient modulus of subgrade soil has been adopted by many transportation agencies following the recommendations of the AASHTO guide for design of pavement structures (AASHTO 1993). Due to the initial lack of consensus on testing protocols and the high cost of equipment, many state agencies, including New England states, have done little testing to establish resilient modulus values of subgrade soils. However, with the AASHTO pavement design guide becoming more mechanistic in its approach, it is

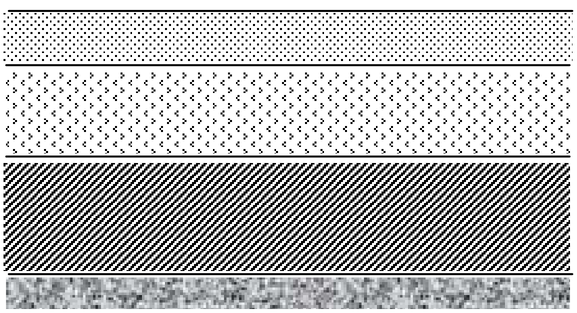


Figure 1. Schematic of a flexible pavement

increasingly important to better quantify the values used for subgrade soil support, namely the resilient modulus of subgrade soils. Even though some scattered research work had been carried by the New England states to determine resilient modulus of subgrade soils in the past, there has not been a comprehensive effort to cover the region as a whole.

1.1. Subgrade Resilient Modulus

Resilient modulus is the elastic modulus based on the recoverable strain under repeated loads, and is defined as

$$M_R = \frac{\sigma_d}{\varepsilon_r} \quad \text{......................................} \quad (1)$$

where, σ_d is the deviator stress, which is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in a triaxial compression test and ε_r is the recoverable strain (see Figure 2).

It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and is proportional to the load and can be considered as elastic.

Figure 2 shows the straining of a specimen under a repeated load test. At the initial stage of load application, there is considerable permanent deformation, as indicated by the plastic strain in the figure. As the number of repetition increases, the plastic strain due to each load repetition decreases. After 100 to 200 repetitions, the strain is practically all recoverable, as indicated by ε_r in Figure 2.

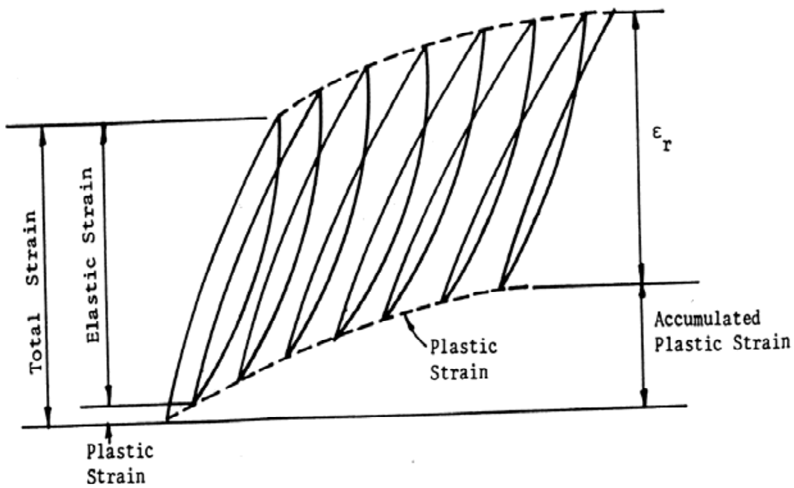


Figure 2. Strains under repeated loads

There are three basic methods that can be used to estimate the resilient modulus value of the subgrade soils (2002 Design Guide). They are:

i. Laboratory repeated load resilient modulus tests
ii. Backcalculation of modulus from Non-Destructive Tests (NDT) data
iii. Correlation of M_R with physical properties of the subgrade soil

According to 2002 Design Guide, repeated load resilient modulus tests are needed for all new designs, particularly for critical projects to assess the effects of changes in moisture on the resilient modulus of a certain soil. However for rehabilitation designs, use of backcalculated elastic modulus has been suggested since it provides data on the response characteristics of the insitu soils and conditions. The point to be noted here is that the design values determined by different methods are different and this difference must be recognized while using these values in the design process.

1.2 Objectives and Scope of Research

The main objective of this research was to develop, based on analysis of relevant existing data and appropriate laboratory validation testing, typical support values (or range of the typical values) for subgrade soils that are found in New England according to AASHTO soil classification.

The major tasks of the project can be summarized as follows:

i. Conduct thorough literature review of work done on resilient modulus and Falling Weight Deflectometer (FWD) studies.
ii. Identify type of subgrade soils in New England states.
iii. Classify subgrades using AASHTO and USCS systems along with soil index properties like moisture content, Atterberg limits, density, gradation etc. which influence resilient modulus (M_R).
iv. Develop prediction models for estimating the values of M_R for different types of New England soils based on the soil properties like moisture content, Atterberg limits, density, gradation, etc.
v. Conduct laboratory M_R tests as per AASHTO specifications on sample New England subgrade soils for verification of the prediction models developed.
vi. Develop a correlation between available backcalculated modulus and M_R values based on the available information, if any.

1.3 Organization of Report

Chapter 1 presents general background information on resilient modulus and the objectives of this research. Chapter 2 presents important conclusions and findings on laboratory resilient modulus and FWD (Falling Weight Deflectometer) backcalculated modulus based on literature review of past research. Results of studies in New England states have been discussed in detail. Chapter 3 outlines the major soil types found in New England states based on United States Department of Agriculture (USDA) soil survey reports.

Chapter 4 presents the laboratory resilient modulus data by AASHTO soil types. Information on M_R data collected from Long Term Pavement Performance Information Management System (LTPP IMS) database used in this study has been provided. Typical laboratory M_R values for 7 AASHTO soil types have been presented in the form of histogram along with the study on variation of M_R with stresses. Three set of resilient modulus prediction models developed for each of 6 AASHTO soil types (A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6) has been presented along with the regression analysis methodology used to develop the models. Chapter 5 contains the prediction models developed by classifying the data collected from LTPP IMS database into USCS soil types Coarse Grained soils and Fine Grained soils.

Chapter 6 presents the data on laboratory M_R tests carried out as a part of this research and experimental verification of prediction models presented in Chapters 4 and 5. Chapter 7 outlines the theory behind calculation of subgrade modulus from falling weight deflectometer test and a brief discussion on the data collected on backcalculated FWD modulus from LTPP database. Summary and Conclusions of this research has been presented in Chapter 8.

Appendix A through Appendix I present many tables and figures giving details of data used from the LTPP database and the results obtained from the current study. These appendices are provided in the attached CD ROM.

2. LITERATURE REVIEW

For several decades, numerous studies have been reported on the subject matter related to subgrade support parameters. Many of the studies deal with direct determination of resilient modulus (M_R) of subgrade soils from the laboratory testing and many other are related to determining other parameters, such as deflections and strength, related to subgrade soils. Since the AASHTO design guide for pavement structures utilizes the resilient modulus value for the subgrade soils as determined by the AASHTO specified laboratory testing, several studies are devoted in developing correlations with, or backcalculation of subgrade moduli from the other measured data.

2.1 Previous Studies on Laboratory Resilient Modulus and FWD Backcalculated Modulus in New England Region

Specific to New England states, some studies have been reported on the determination of resilient modulus of limited numbers of subgrade soils in Connecticut (Long and Delgado 1991, Long and Crandlemire 1992), in Maine (Smart and Humphrey 1999), in New Hampshire (Janoo et al 1999), and in Rhode Island (Kovacs 1991; Lee et al 1994, 1997). Excerpts of studies on laboratory resilient modulus tests and FWD tests in Connecticut, New Hampshire, Rhode Island and Maine have been presented below:

- **Connecticut:** Long and Crandlemire (1992) studied the effects of moisture content, drainage conditions, confining stress and bulk stress on M_R for 3 Connecticut soils. Two soils showed a trend of decreasing M_R with increasing moisture content. One soil exhibited decrease in M_R moving from the optimum moisture content to the wet of this value. Tests performed to compare the value of M_R in drained and undrained states showed only minor differences between the two cases. Confining pressure model ($M_R = k1(\sigma c)^{k2}$) and Bulk stress model ($M_R = k3(\theta)^{k4}$), where σc is confining stress and θ is bulk stress and k1, k2, k3, and k4 are regression coefficients were studied. The confining stress model was found to yield a higher correlation coefficient than the bulk stress model which indicates that the confining pressure model is more accurate.

- **New Hampshire:** Janoo et al. (1999) suggested effective resilient modulus (M_R) values for use in design and evaluation of pavement structures based on resilient modulus tests conducted on 5 subgrade soils commonly found in New Hampshire. The effective M_R values have been presented in Table 1 below along with some soil properties. These M_R values were obtained at the optimum density and moisture content so should be used with reservation at other densities and moisture contents.

Table 1. M_R for New Hampshire Subgrade Soils

Soil Designation	AASHTO Class.	USCS Class.	Optimum Moisture (%)	Density kg/m^3 (pcf)	Effective M_R MPa (psi)
Silt, some fine sand. Some coarse to fine gravel, trace coarse to medium sand (glacial till) – NH1	A-4	SM	9.0	2050 (128)	45 (6500)
Fine sand, some silt – NH2	A-2-4	SM	14.5	1714 (107)	62 (9000)
Coarse to fine gravel, coarse to medium sand, trace fine sand – NH3	A-1-a	SP	9.5	1730 (108)	265 (38,500)
Coarse to medium sand, little fine sand – NH4	A-1-b	SP	13.6	1642 (102.5)	26 (3800)
Clayey silt (marine deposit) – NH4	A-7-5	ML	23.5	1618 (101)	21 (3000)

- **Rhode Island:** Lee et al. (1994) conducted resilient modulus tests on subgrade soils from 8 different sites in Rhode Island. It was observed that at normal and thawed conditions, M_R increased as the bulk stress increased. This relationship was not clearly apparent at frozen conditions. It was also seen that at constant temperature, M_R decreased with increase in moisture content. Prediction equations developed for subgrade soils yielded average effective M_R of 5 ksi with standard deviation of 1.1 ksi. The average ratio of backcalculated moduli to the M_R from prediction equations was found to be 2.88 with a standard deviation of 0.49. The analysis of Falling Weight Deflectometer (FWD) data indicated only limited influence of seasonal variations on the modulus of subgrade soils.

The subgrade types and their classification along with their properties for the Rhode Island soils are given in Table 2.

Table 2. M_R and FWD modulus for Rhode Island Subgrade Soils

Site	AASHTO Class.	USCS Class.	Passing No. 200 (%)	OMC (%)	Max. Dry Density (pcf)	CBR	M_R (psi)	FWD Back-calculated Modulus (psi)
Rt. 2	A-1-b	SW	10.0	6.9	133.4	17	13000	22600
Rt. 146	A-1-b	SW	10.0	7.8	131.7	24	13400	24600
UCR (N)	A-1-b	CL-ML	60.7	6.4	132.1	16	10400	14300
RWW	A-3	SP-SM	8.9	9.3	121.2	9	9800	
Rt. 107	A-1-b	SP-SM	7.3	6.3	137.9	25	13400	
Jamestown	A-1-b	SW-SM	7.2	8.6	126.0	9	12000	
Charles St.	A-1-b	SM	11.3	10.0	122.6	14	13200	
Rt. 146S	A-1-b	SC	20.8	6.1	134.7	11	13100	

Maine: Smart and Humphrey (1993) carried out their study for Maine roadway soils. They suggested that useable correlations of M_R with soil properties and stress states can be developed and proposed prediction equations for M_R in terms of index properties (dry density, degree of saturation, % passing, optimum water content) by conducting linear regression analysis. The K_n constants for several constitutive equations were calculated for 14 Maine soils. These constants can be used for soils with similar classification, dry density and water content. They also observed that the accuracy of M_R depended on test equipment and operator skill.

2.2 Other Studies on Laboratory Resilient Modulus

Several studies have been carried out to quantify the value of M_R for different types of soils and evaluate the effect of various soil properties. It has been seen that M_R is not a constant stiffness property, but depends on various factors like soil physical properties such as moisture content, density, plastic limit, liquid limit, plasticity index, soil type and stress states like deviator stress and confining stress (George 2004). Different researchers have pointed out different factors to be affecting M_R. Majority of them have observed that moisture content have significant effect on the value of M_R. In their study to find out factors influencing determination of M_R value, Burczyk et al. (1995), observed that, M_R value decreased as water content increased for A-4 and A-6 soils while A-7 subgrade soils showed little change with change in water content. During their research to assess the seasonal variation of M_R for subgrade soils, Jin et al. (1994) observed that M_R increases as the moisture content and temperature decreases, and dry density increases.

Regarding the stress states, research has shown that M_R increases with increase in confining stress (George 2004). Also, for fine-grain soils M_R decreases with increase in deviator stress and for granular materials, M_R increases slightly with increase in deviator stress. Several constitutive models have been developed in the past for M_R of subgrade soils which relate M_R to the stress states. Santha (1994), from his study on the M_R of subgrade soils concluded that the universal model $M_R = k_1Pa(\theta/Pa)^{k_2} (\sigma_d/Pa)^{k_3}$, (where θ=bulk stress, σ_d=deviator stress, Pa= atmospheric pressure and k_1, k_2, k_3=material physical property parameters) is capable of describing the behavior better than the bulk stress model $M_R=k_1Pa(\theta/Pa)^{k_2}$, (where θ=bulk stress, Pa= atmospheric pressure and k_1, k_2, k_3=material physical property parameters) for granular soils. Mohammad et al. (1999) in a similar study to establish a regression model for M_R of subgrade soils found that the octahedral stress state model ($M_R/ \sigma_{atm}=k_1(\sigma_{oct}/\sigma_{atm})^{k_2} (\tau_{oct}/\sigma_{atm})^{k_3}$, where σ_{oct} , τ_{oct} = octahedral normal and shear stresses respectively, σ_{atm} = atmospheric pressure, and k_1, k_2, k_3=model constants) interprets M_R tests results better than the simple bulk stress ($M_R=a(\theta)^b$, where θ=bulk stress, and a,b=model constants) and deviator stress ($M_R=c(\sigma_d)^{d_1}$, where σ_d=deviator stress, and c,d_1=model constants) models. Experimental results of Dai and Zollars (2002) showed that the universal model described M_R slightly better than the deviator stress model for the tests conducted on subgrade soils collected at 6 different pavement sections in Minnesota.

2.3 Other Studies on FWD Backcalculated Modulus

Deflection measurements have long been used to evaluate the structural capacity of insitu pavements. They can be used to backcalculate the elastic moduli of various pavement components, evaluate the load transfer efficiency across joints and cracks in concrete pavements, and determine the location and extent of voids under concrete slabs. Many mechanical devices are being used to perform nondestructive testing (NDT) on pavements. Based on the type of loading applied to the pavement, NDT deflection testing devices can be divided into three categories: (1) static or slowly moving loading devices (e.g. the benkelman beam, California traveling deflectometer and LaCroix deflectometer); (2) steady-state vibratory devices (e.g. Dynaflect and Road Rater); and (3) impulsive (transient) load devices (e.g. various falling weight deflectormeters, FWD). Some of the FWD type devices currently commercially available are: Dynatest, KUAB, and Pheonix Falling Weight Deflectometer. Also in recent years extensive investigation is directed toward Portable Falling Weight Deflectometer (PFWD) devices (Livneh 1997, Livneh et al 1997, and Sickmaier et al 2000). There is also a simplified alternative test method (ATM), a laboratory test apparatus that closely resembles a common nondestructive field testing FWD developed (Drumm et al. 1995). In general, the falling weight deflectometer is the best NDT device developed that simulate the magnitude and duration of actual moving vehicle loads (Lytton 1989). Other non destructive testings which do not directly measure the deflection, but do measure the pavement performance and damage include use of wave propagation, impact hammer, ground-penetrating radar, and impedance devices.

The subgrade modulus value often called the backcalculated modulus can be determined from the FWD measurements using the backcalculation software packages like MODULUS, MODCOMP, EVERCALC, WESDEF, WESNET, MICHBACK, FWD-DYN, etc.

Several researchers have studied the relationship between the backcalculated modulus and the laboratory resilient modulus in the past. Most researchers have observed that the backcalculated modulus is almost always greater than the laboratory determined modulus value at the same site at comparable stress states and/or temperatures. A summary of the past studies on the ratio between the backcalculated modulus and laboratory resilient modulus have been presented in Table 3.

2.4 LTPP study on Laboratory Resilient Modulus and FWD Backcalculated Modulus

The Long Term Pavement Performance (LTPP) program is a 20-year program, which was initiated in 1987 as a part of Strategic Highway Research Program (SHRP). Today, the program has more than 2400 test sections on in-service highways at over 900 locations throughout North America (www.datapave.com). This database has a huge amount of test results on laboratory M_R, soil index properties and FWD Backcalculated Modulus that facilitate study of many subgrade soil behaviors. Also the results from the study using the LTPP data can make a good basis to verify accuracy and validate other independent studies. Some of the studies conducted using the data from LTPP tests include study on laboratory resilient modulus, backcalculated pavement moduli, effect of moisture on pavement perfomance (Yau and Von Quintus 2002, Von Quintus and Killingsworth 1998).

In the present study data from LTPP database was used to investigate on resilient modulus and FWD backcalculated modulus of subgrade soils. Prediction models were developed in this study for 6 AASHTO soil types using the laboratory M_R test data and the soil physical properties data available in the LTPP database.

Table 3. Summary of literatures on relationship between FWD Backcalculated and Laboratory measured Resilient Moduli

State	Author	$E(FWD)/M_R(Lab)$	FWD Backcalculation Software Used
	AASHTO Guide for Design of Pavement Structures, 1993	3.03	
Kansas	H.S. Russell, M. Hossain, 2000	3.03	EVERCALC
Wyoming	J.M. Burczyk et al, 1995	2.564 4 3.226	MODULUS EVERCALC BOUSDEF
North Carolina	N.A. Ali, N.P. Khosla, 1987	0.409 to 5.55	VESYS, ELMOD, OAF
Mississippi	A. Rahim, K.P. George, 2003	Without Pavement Structure: Fine-grain Soil: 1.10 – Average (Range - 0.80 to 1.30) Coarse-grain Soil: 1.03 – Average (Range - 0.80 to 1.2) With Pavement Structure: Fine-grain Soil: 1.40 – Average (Range – 0.85 to 2.0) Coarse-grain Soil: 2.40 (Range – 0.90 to 2.40) LTPP Data Analysis: (With Pavement Structure) Fine-grain Soil: 1.70 – Average (Range - 0.80 to 2.60) Coarse-grain Soil: 1.90 – Average (Range – 1.20 to 2.50)	MODULUS 5
Florida	W.V. Ping, Z. Yang, Z. Gao, 2002	1.6	MODULUS 5
North Atlantic & Southern SHRP regions	J.F. Daleiden et al, 1994	1.754 - Mean (Range: 0.097 to 100 - --- did not generate any useful relationships)	MODULUS 4
Washington	D.E. Newcomb, 1987	0.769 to 1.25	Chevron N-Layer Program
Arizona	Houston et al, 1992	1.5 (Average)	Not Mentioned

3. SUBGRADE SOIL TYPES IN NEW ENGLAND STATES

Subgrade soils in New England have been classified here in this report according to American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System and Unified Soil Classification Systems (USCS). The criteria for these classifications and types of subgrades in New England region have been presented in sections below.

3.1 General Soil Classification Systems

The criteria for classification of subgrades based on American Association of State Highway and Transportation Officials (AASHTO) (Das 1999) and Unified Soil Classification Systems (USCS) (Zayach and Ellyson 1959) are presented in Tables 4 and 5 respectively. Table 5 also lists the AASHTO classifications corresponding to a particular USCS soil type.

Table 4. AASHTO soil classification system

General Classification	**Granular materials (35 % or less of total sample passing No. 200 sieve)**						
	A-1		A-3	A-2			
Group classification	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7
Sieve Analysis (% Passing) No. 10 sieve No. 40 sieve No. 200 sieve	50 max 30 max 15 max	50 max 25 max	51 min 10 max	35 max	35 max	35 max	35 max
For fraction passing No. 40 Sieve Liquid Limit (LL). Plasticity Index (PI)	6 max	6 max	Non-plastic	40 max 10 max	41 min 10 max	40 max 11 min	41 min 11 min
Usual type of material	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand			
Subgrade rating	Excellent to good						

Table 4. AASHTO soil classification system *(Cont'd…)*

General Classification	**Silty-clay materials (More than 35 % of total sample passing No. 200 sieve)**			
Group classification	A-4	A-5	A-6	A-7 A-7-5[a] A-7-6[b]
Sieve Analysis (% passing) No. 10 sieve No. 40 sieve No. 200 sieve	 36 min	 36 min	 36 min	 36 min
For fraction passing No. 40 sieve Liquid Limit (LL) Plasticity Index (PL)	 40 max 10 max	 41 min 10 max	 40 max 11 min	 41 min 11 min
Usual types of material	Mostly silty soils		Mostly clayey soils	
Subgrade rating	Fair to poor			
[a] If PI ≤ LL – 30, it is A-7-5. [b] If PI > LL – 30, it is A-7-6.				

3.2 Soil Classification of New England States

AASHTO and USCS soil classifications of subgrades in New England States based on United States Department of Agriculture (USDA) soil survey reports have been presented in this report. USDA Soil Conservation Service in co-operation with the state agencies has conducted the soil survey in different parts of the country. The soil survey has been reported county by county for Connecticut (CT), Maine (ME), Massachusetts (MA), New Hampshire (NH), and Vermont (VT) whereas for Rhode Island (RI), the soil types for the entire state has been reported (Appendix A in attached CD ROM). The USDA reports contain the various types of soil and their variation with depth in a tabular form. It also consists of soil maps of a county.

A consolidated table consisting of the type of subgrades found in each of the six New England states (CT, ME, MA, NH, VT, RI) has been presented in Table 6 below. The soils types shown in bold indicate the most predominant soils types in that region.

To classify the type of subgrade at a given place, the soil type existing in only the top 1 ft was considered. Both the USCS and AASHTO classification of subgrade along with plasticity index and liquid limit are shown county by county for Connecticut, Maine, Massachusetts, New Hampshire, Vermont and for the entire state for Rhode Island in Tables A.1, A.2, A.3, A.4, A.5 and A.6, respectively (Appendix A in attached CD ROM) .

Table 5. USCS classification compared with AASHTO classification

Major divisions	Group Symbol	Value as Foundation Material	Soil description	Max. dry density: Aprox. Range in AASHTO *lb/cu.ft*	Field CBR	Subgrade Modulus, k	Comparable groups AASHTO classificat-ion
Coarse-grained soils (50 percent or less passing No. 200 sieve)							
Gravels and gravelly soils (more than half of coarse fraction retained on No. 4 sieve)	GW	Excellent	Well-graded gravels and gravels-sand mixtures; little or no fines	125-135	60-80	300+	A-1
	GP	Good to excellent	Poorly graded gravels and gravel-sand mixtures; little or no fines	115-125	25-60	300+	A-1
	GM	Good	Silty gravels and gravel-sand-silt mixtures	120-135	20-80	200-300+	A-1 or A-2
	GC	Good	Clayey gravels and gravel-sand-clay mixtures	115-130	20-40	200-300	A-2
Sands and sandy soils (more than half of coarse fraction passing No. 4 sieve)	SW	Good	Well-graded sands and gravelly sands; little or no fines	110-130	20-40	200-300	A-1
	SP	Good	Poorly graded sands and gravelly sands; little or no fines	100-120	10-25	200-300	A-1 or A-3
	SM	Fair to good	Silty sands and sand-silt mixtures	110-125	10-40	200-300	A-1, A-2 or A-4
	SC	Fair to good	Clayey sands and sand-clay mixtures	105-125	10-20	200-300	A-2, A-4 or A-6

Table 5. USCS Classification compared with AASHTO classification *(Cont'd...)*

Major divisions	Group Symbol	Value as Foundation Material	Soil description	Max. dry density: Aprox. Range in AASHTO *lb/cu.ft*	Field CBR	Subgrade Modulus, k	Comparable groups AASHTO classifica-tion
Fine-grained soils (more than 50 percent passing No. 200 sieve)							
Silts and Clays (liquid limit of 50 or less)	ML	Fair to poor	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, and clayey silts of slight plasticity	95-120	5-15	100-200	A-4, A-5 or A-6
	CL	Fair to poor	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, and lean clays	95-120	5-15	100-200	A-4, A-6 or A-7
	OL	Poor	Organic silts and organic clays having low plasticity	80-100	4-8	100-200	A-4, A-5, A-6 or A-7
Silts and Clays (liquid limit greater than 50)	MH	Poor	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, and elastic silts.	70-95	4-8	100-200	A-5 or A-7
	CH	Poor to very poor	Inorganic clays having high plasticity and fat clays	75-105	3-5	50-100	A-7
	OH	Poor to very poor	Organic clays having medium to high plasticity and organic silts	65-100	3-5	50-100	A-5 or A-7
Highly Organic Soils	Pt	Not suitable	Peat and other highly organic soils	------------	-------	----------	None

Table 6. Soil types in New England States

State	**AASHTO Classification**	**USCS Classification**	**Plasticity Index**	**Liquid Limit (%)**
Connecticut	A-1, A-1-b, **A-2**, A-3, **A-4**, A-5, A-6, A-7	SM, ML, OL, SM-SC, MH, OH, CL, SP-SM, Pt, CL-ML, SW-SM	NP-10	<45
Maine	**A-1, A-1-b, A-2, A-3, A-4**, **A-5**, **A-6**, A-7, A-7-5	**SM, ML, SC, GM, CL, OL**, SP-SM, **SW-SM**, GW, GP, SW, SP, **SM-SC**, **SP**, **GM-GC**, **CL-ML**, GW-GM, GP-GM, SP, **MH**, OH	NP-40	<57
Massachusetts	**A-1**, A-1-b, **A-2**, A-2-4, **A-3**, **A-4, A-5, A-6**, A-7, A-8	**SP, SM, SP-SM, ML**, Pt, **GM, CL-ML, SC, SM-SC**, GC, CL, GP-GM, SW, GW, OL, **SW-SM**, MH, GW-GM, MH-CH, **GM-GC**	NP-44	<60
New Hampshire	**A-1, A-1-b, A-2,** A-2-4, A-3, **A-4,** A-5, A-6, A-7, A-8	**SM, ML**, SP-SM, GP-GM, GM, **CL-ML, SC-SM**, SW-SM, **SC**, GM, Pt, SP, GP, **CL**, GM-GC, **MH**	NP-25	<60
Rhode Island	A-1, A-2, A-3, A-4, A-7, A-8	CL, SC, Pt, ML, SP-SM, GM, OL, SM-SC, GP-GM, CL-ML	NP-12	<45
Vermont	**A-1**, **A-2, A-2-4,** A-2-5, A-3, **A-4**, A-5, **A-6, A-7-5**	**SM,** SP-SM, SP, **ML,** GP-GM, **GM**, SW-SM, GW-GM, GM, GW, **CL**, **SC**, **CL-ML**, SM-SC, MH-CH, OL, SP-SM, GC, OH, SM	NP-65	<65

Note: NP = Nonplastic

4. RESILIENT MODULUS BY AASHTO SOIL TYPES

In order to analyze the resilient modulus (M_R) value of subgrade soils, data on large numbers of laboratory M_R tests results are required. In this study, data on laboratory resilient modulus and FWD backcalculated modulus was extracted from the Long Term Pavement Performance (LTPP) Information Management System (IMS) Data, Release 15.0, January 2003 Upload. Results of 300 M_R (approximately 4500 M_R values) tests were extracted from the LTPP database. This database includes extensive data on material testing, pavement performance monitoring, traffic, maintenance, rehabilitation, and seasonal testing (www.datapave.com).

In this study data for 19 states in the New England, Northern Mid Atlantic, Great Lakes, and Upper Midwest regions and 2 provinces in Canada was extracted from the LTPP database. They include:

New England region - Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. Lab M_R test data is not available for New Hampshire and Rhode Island.

Northern Mid Atlantic region - New Jersey, New York, Pennsylvania.

Great Lakes region - Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin, Ontario, and Quebec.

Upper Mid West region - Iowa, Kansas, Missouri, Nebraska, North Dakota, and South Dakota.

4.1 Resilient Modulus Values for Different AASHTO Soil Types from LTPP Database

The data collected from LTPP database includes data for 8 AASHTO subgrade soil types namely, A-1-b, A-3, A-2-4, A-2-6, A-4, A-6, A-7-5, and A-7-6. Soils of class A-1-a, A-2-5, A-2-7, and A-5 were not found in the test sites considered here in this report. A list of LTPP test sites where laboratory resilient modulus (M_R) and field FWD test data were available in the database are given in Appendix B (in accompanying CD.) All raw data extracted from LTPP database have been presented in Appendix I (in accompanying CD). Number of soil samples for which information is available in the LTPP database and collected for this study in each of the states considered (see list above) has been presented in Table 7. The soil samples include disturbed as well as undisturbed samples. Histograms and percentage cumulative frequency curves for the laboratory M_R values for the 7 soil types A-1-b, A-3, A-2-4, A-2-6, A-4, A-6, and A-7-6 have been shown in Figure 3 through Figure 16. Soil type A-7-5 is not included in this study hereafter, since, test result of only one soil sample was available in the LTPP database for the regions considered.

Table 7. Total number of soil samples by states for which data collected from LTPP database

State	State Code	AASHTO Soil Classification											
		A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5	A-7-6
New England													
Connecticut	9	-	-	-	3	-	-	-	-	-	-	-	-
Maine	23	-	2	1	4	-	-	-	-	-	-	-	-
Massachusetts	25	-	1	1	-	-	-	-	-	-	-	-	-
New Hampshire	33	-	-	-	-	-	-	-	-	-	-	-	-
Rhode Island	44	-	-	-	-	-	-	-	-	-	-	-	-
Vermont	50	-	-	-	3	-	-	-	2	-	-	-	1
Northern Mid Atlantic													
New Jersey	34	-	4	1	3	-	-	-	-	-	-	-	-
New York	36	-	1	1	3	-	-	-	2	-	-	-	-
Pennsylvania	42	-	2	-	8	-	1	-	11	-	3	-	-
Great Lakes													
Illinois	17	-	1	1	1	-	-	-	11(2)	-	2(1)	-	1
Indiana	18	-	1	1	4	-	-	-	7(2)	-	3(1)	-	1
Michigan	26	-	2	8(1)	1	-	-	-	7	-	4	-	-
Minnesota	27	-	12	2	6	-	2(1)	-	2	-	5(2)	1	1
Ohio	39	-	-	-	-	-	-	-	9	-	6	-	3
Wisconsin	55	-	3	4	-	-	-	-	2	-	1	-	-
Ontario	87	-	-	-	-	-	-	-	8	-	1	-	-
Quebec	89	-	-	4	7	-	-	-	-	-	-	-	-
Upper Mid West													
Iowa	19	-	-	-	4	-	-	-	5(3)	-	11(6)	-	-
Kansas	20	-	-	1	3	-	-	-	6(1)	-	4(2)	-	9(4)
Missouri	29	-	2	-	-	-	3	-	6(1)	-	4(1)	-	6(1)
Nebraska	31	-	2	-	2	-	-	-	8	-	4	-	7(3)
North Dakota	38	-	-	-	-	-	-	-	2	-	-	-	-
South Dakota	46	-	1	-	-	-	-	-	6(1)	-	7(2)	-	4
Total		0	34	25(1)	52	0	6	0	94(10)	0	55(15)	1	33(8)
* Numbers in parentheses are the number of undisturbed samples													

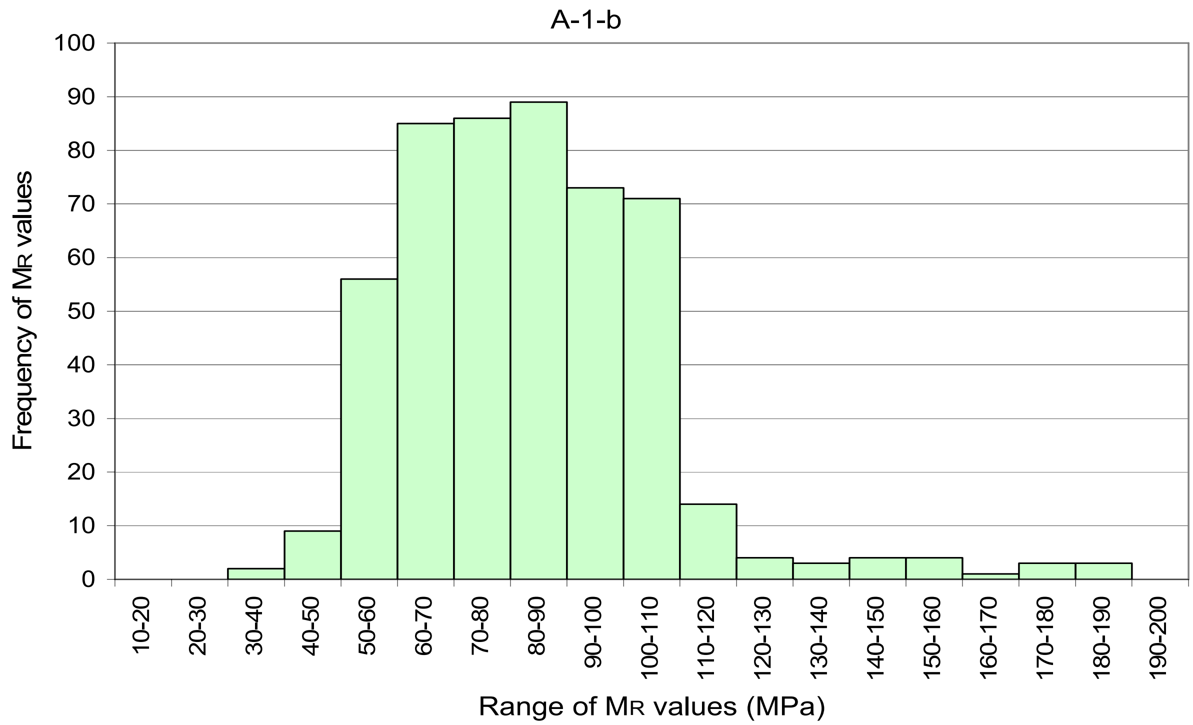


Figure 3. Histogram of laboratory M_R values for A-1-b soils

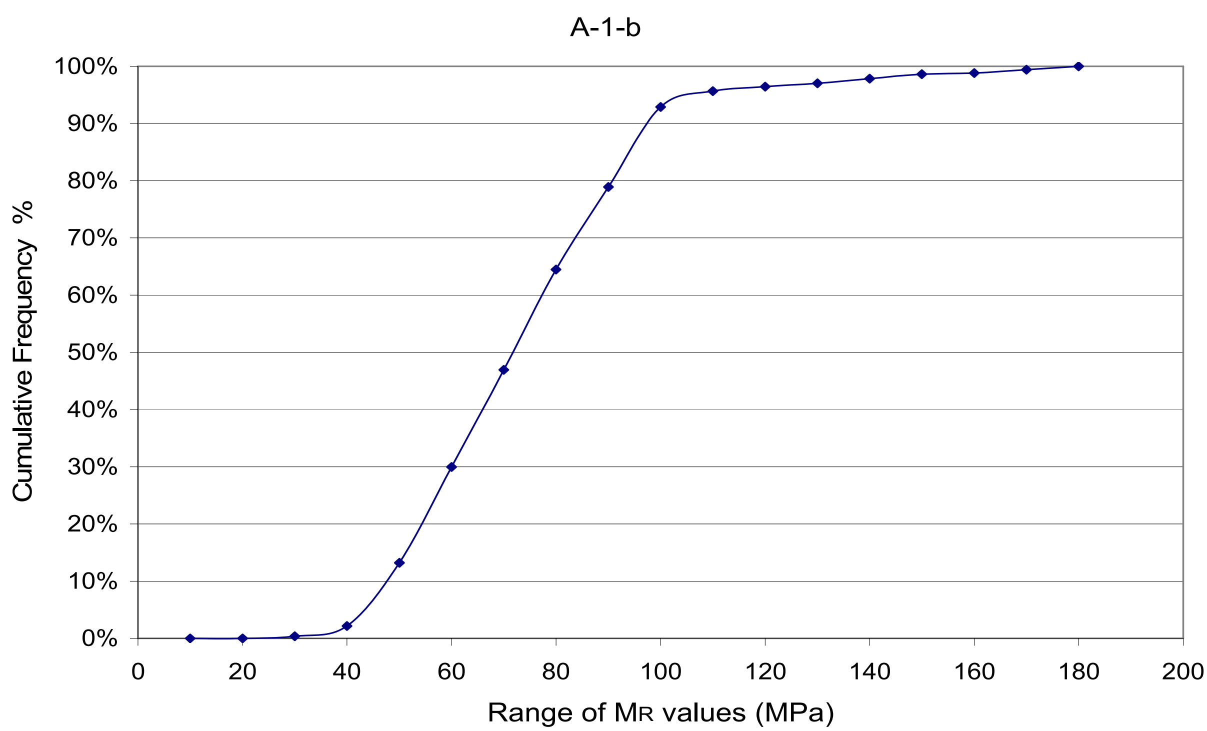


Figure 4. Percentage cumulative frequency curve for A-1-b soils

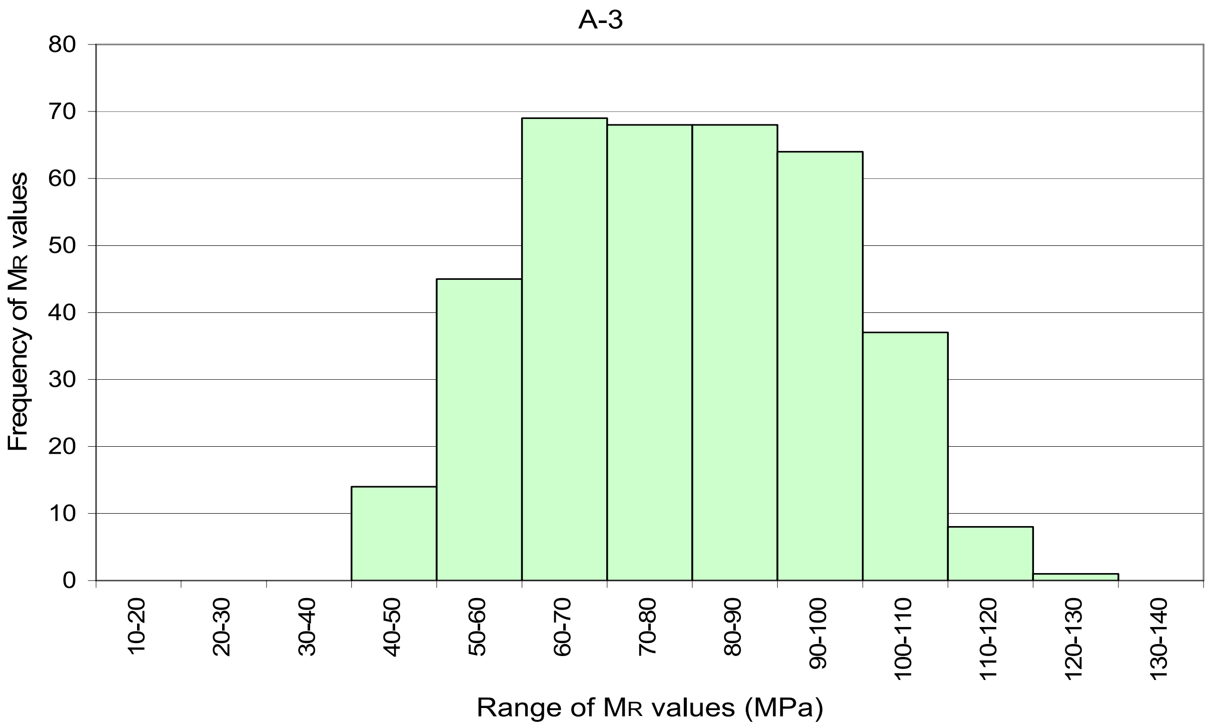


Figure 5. Histogram of laboratory M_R values for A-3 soils

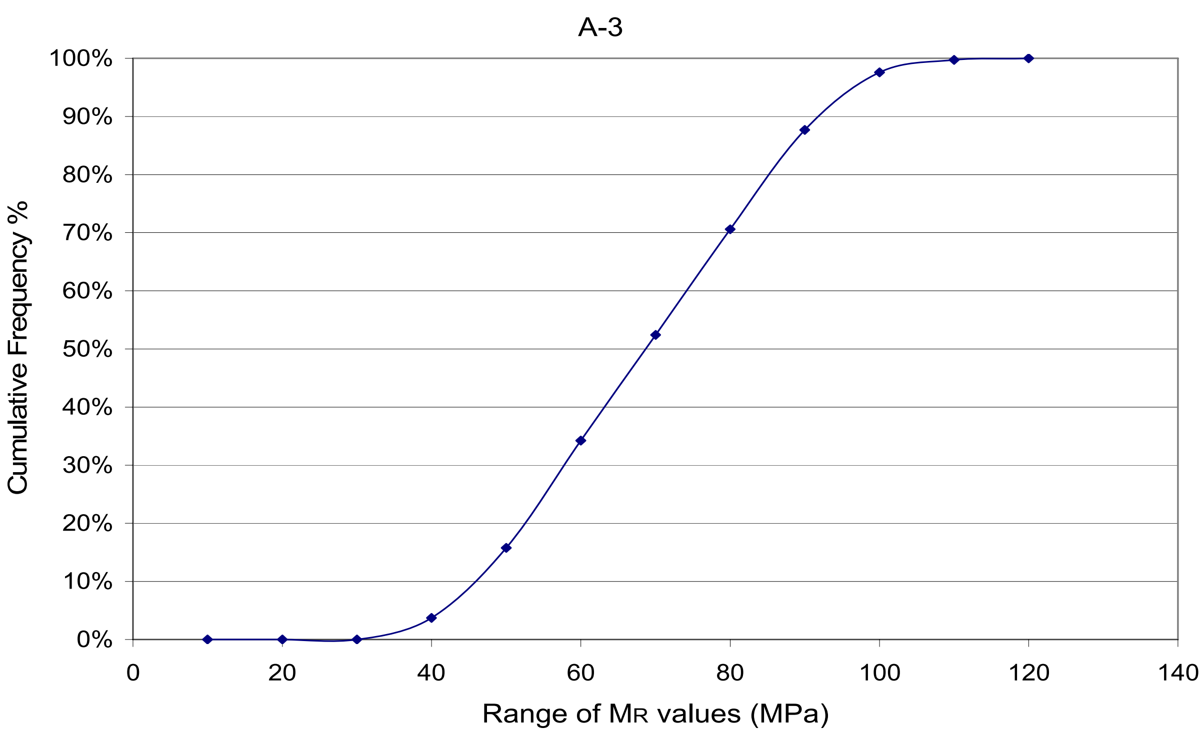


Figure 6. Percentage cumulative frequency curve for A-3 soils

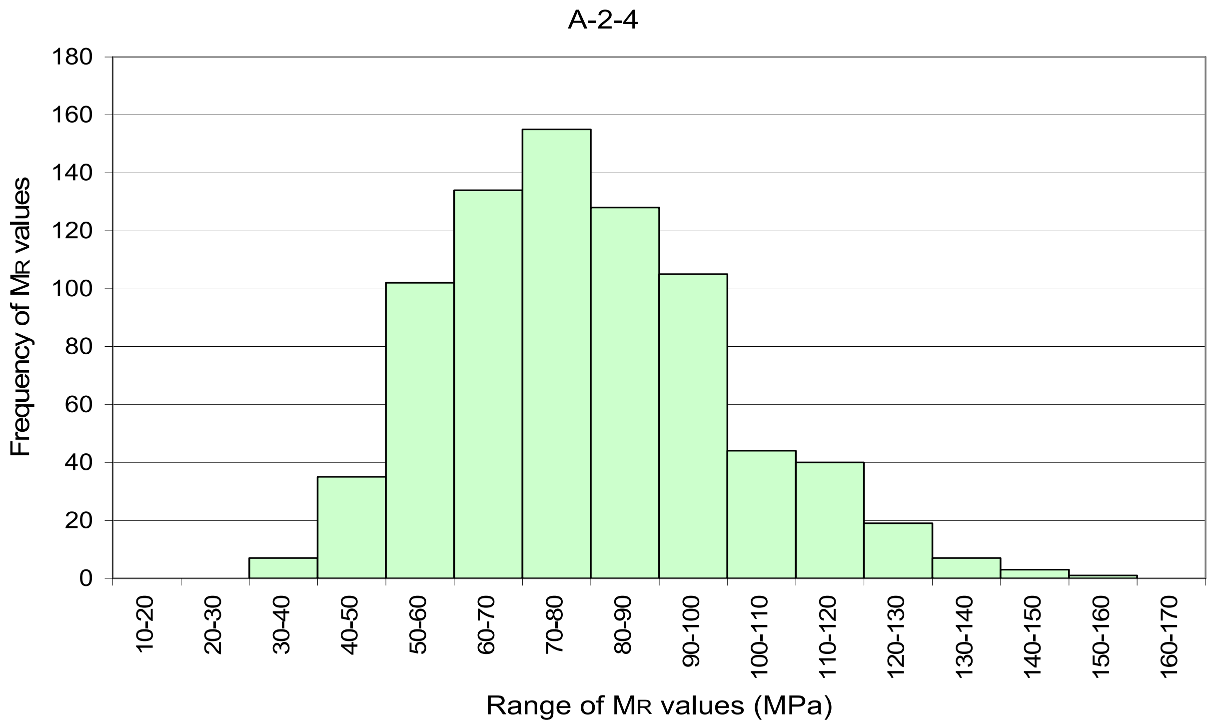


Figure 7. Histogram of laboratory M_R values for A-2-4 soils

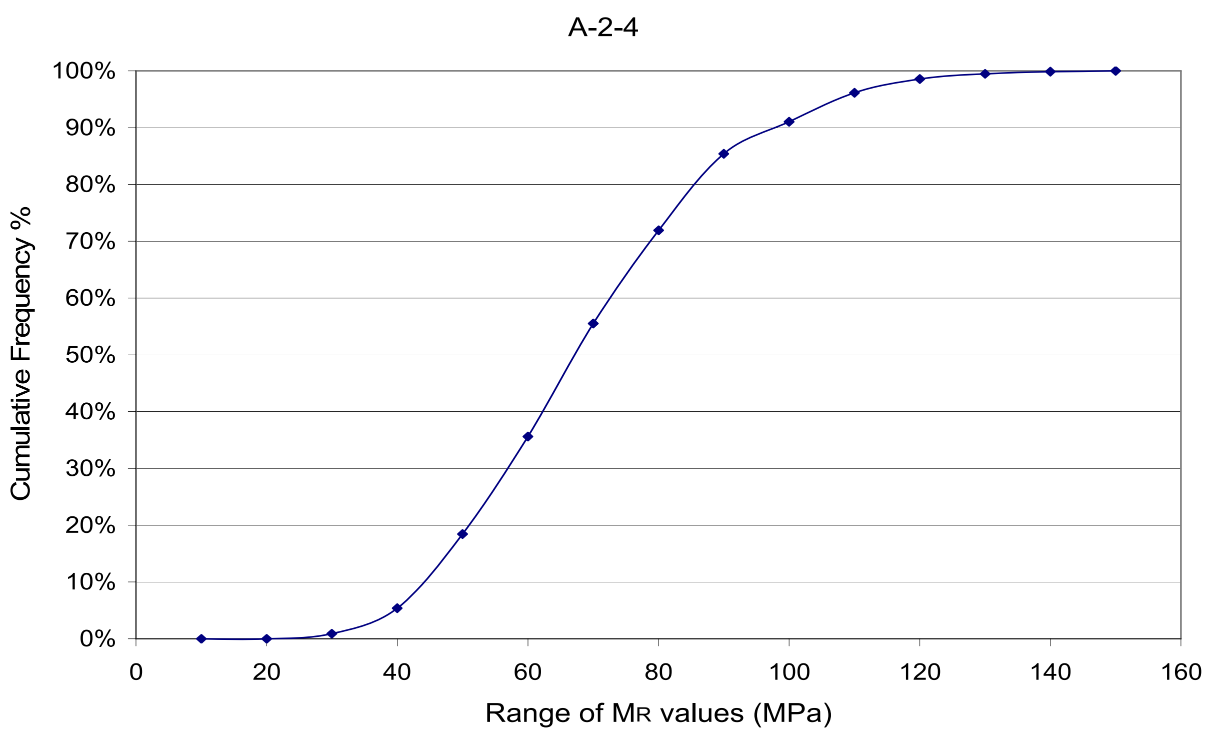


Figure 8. Percentage cumulative frequency curve for A-2-4 soils

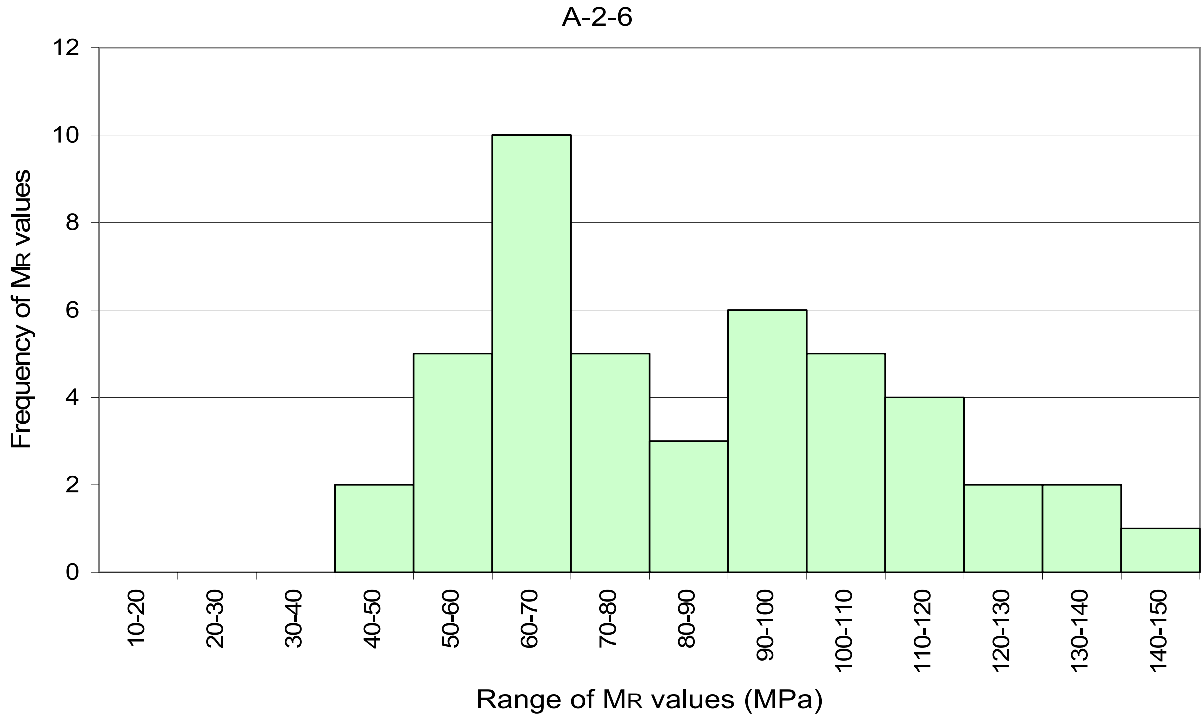


Figure 9. Histogram of laboratory M_R values for A-2-6 soils

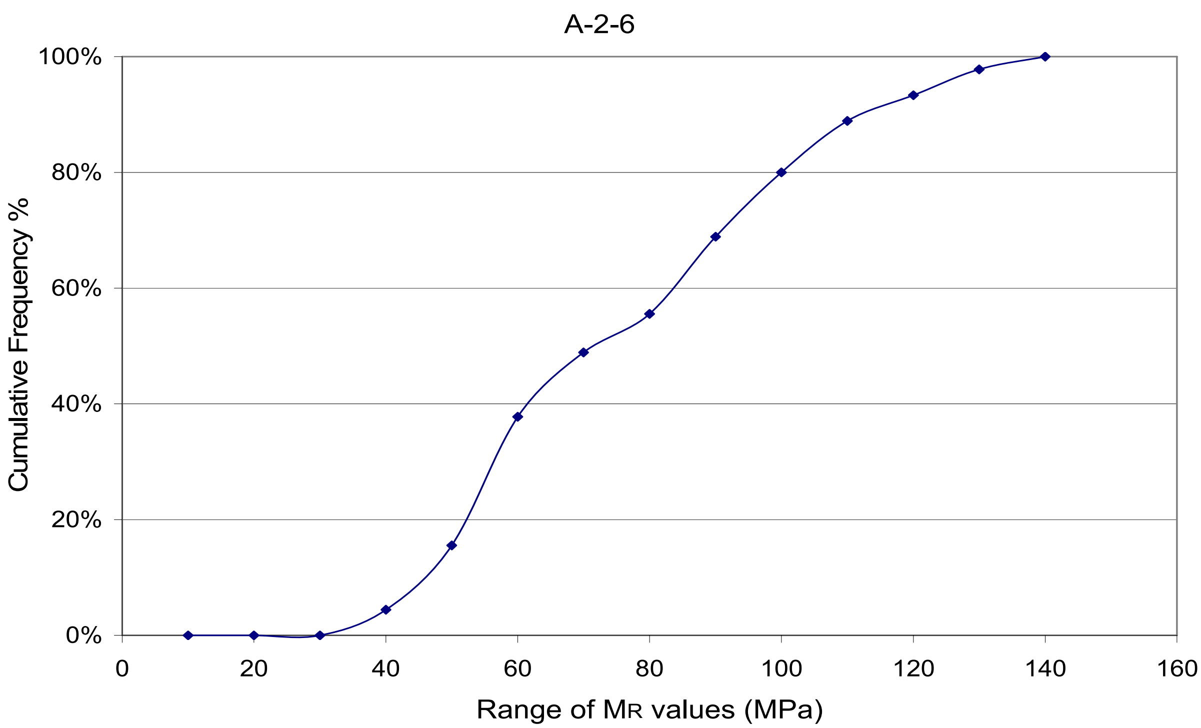


Figure 10. Percentage cumulative frequency curve for A-2-6 soils

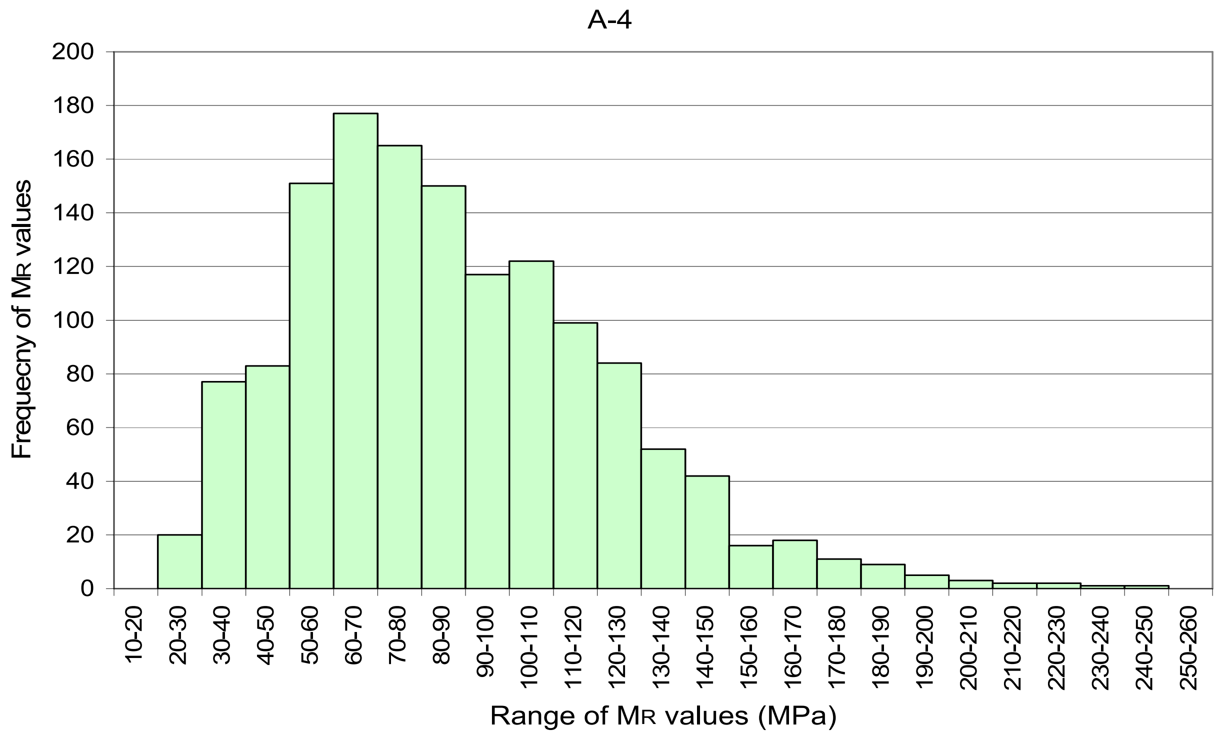


Figure 11. Histogram of laboratory M_R values for A-4 soils

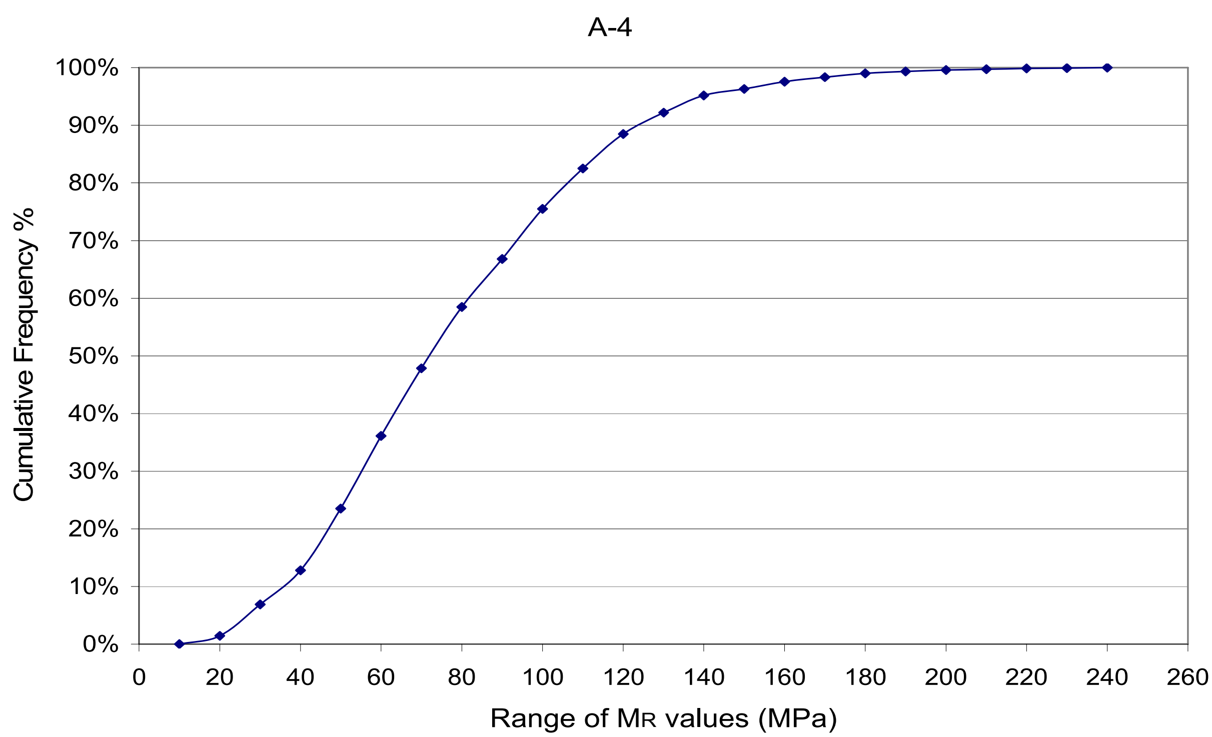


Figure 12. Percentage cumulative frequency curve for A-4 soils

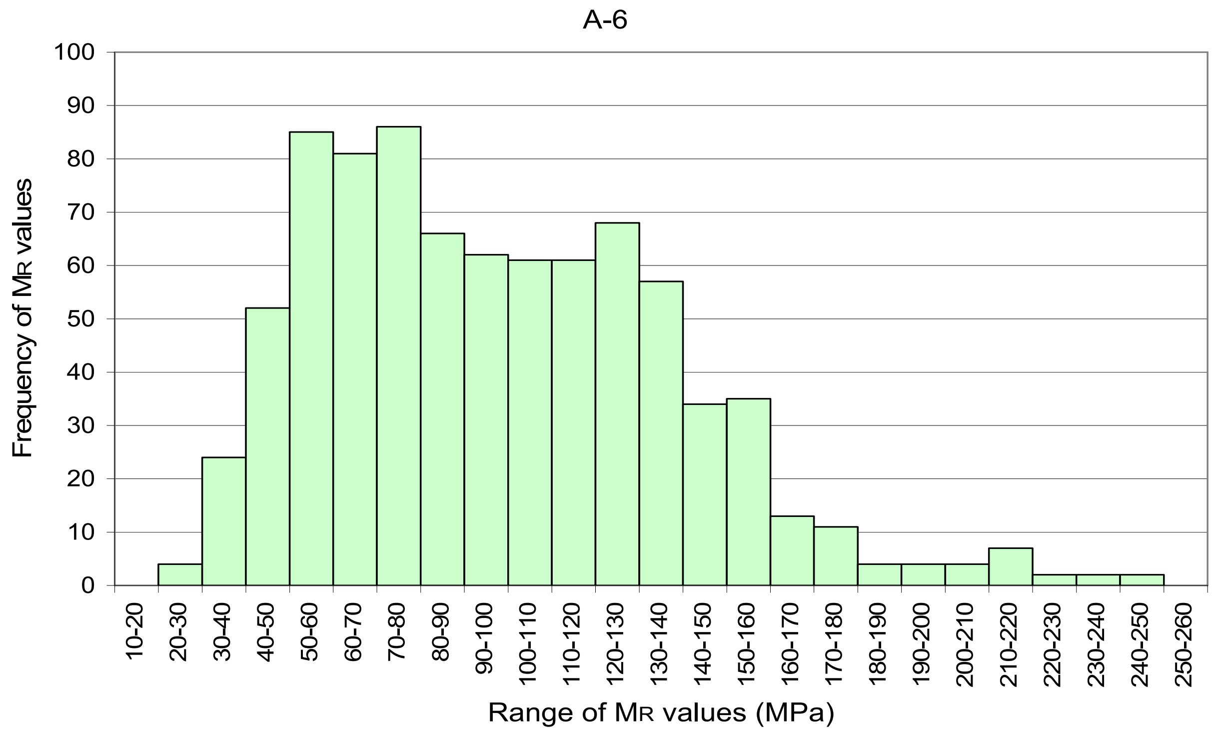


Figure 13. Histogram of laboratory M_R values for A-6 soils

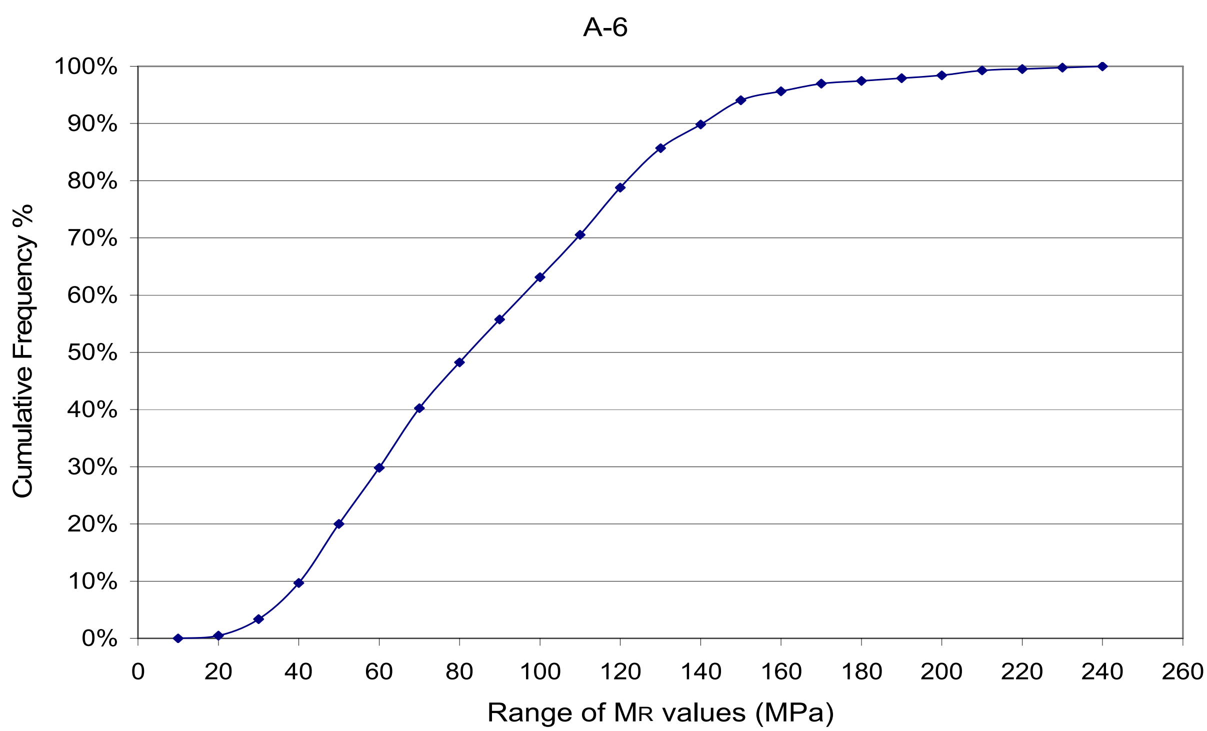


Figure 14. Percentage cumulative frequency curve for A-6 soils

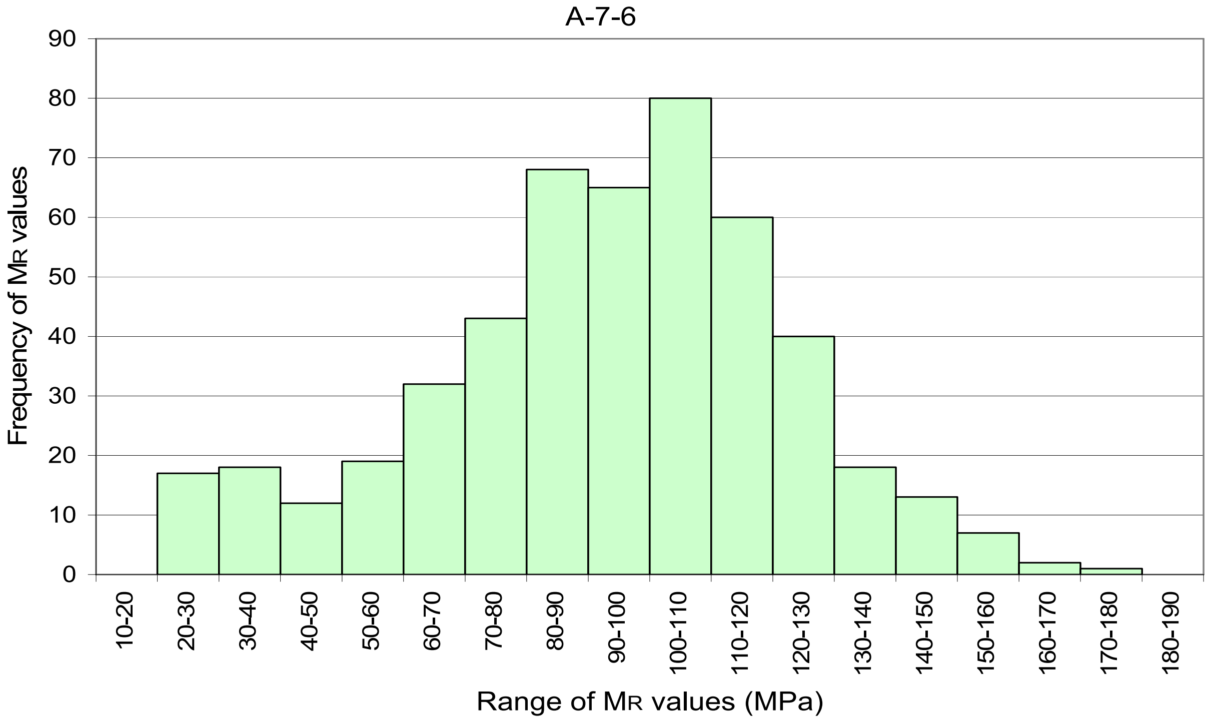


Figure 15. Histogram of laboratory M_R values for A-7-6 soils

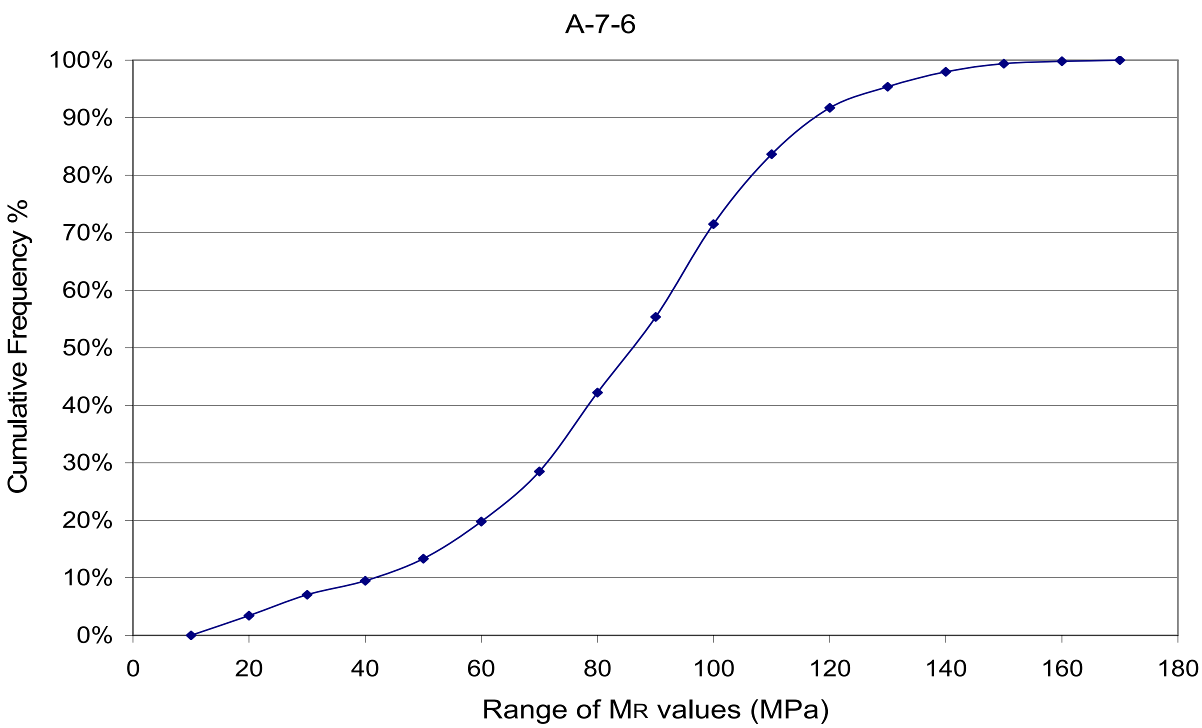


Figure 16. Percentage cumulative frequency curve for A-7-6 soils

4.2 Variation of Resilient Modulus (M_R) with Stress Levels

During the laboratory resilient modulus test, the test specimen is subjected to 5 levels of cyclic stress (approximately 12.4, 24.8, 37.3, 49.7, and 62.0 kPa) at each of the 3 levels of confining pressure (13.8, 27.6, 41.4 kPa). Previous studies have shown that M_R varies with the change in stresses. To investigate this effect, for the data extracted from LTPP database, resilient modulus values were plotted against the nominal maximum axial stress and confining pressure for certain number of representative soil samples in each of the 7 AASHTO subgrade soil types mentioned in earlier section. The results are given in Figures 17 through 32. It was observed that for the granular soils like A-1-b, A-3, and A-2-4, M_R usually increased with increase in nominal maximum axial stress at the same level of confining pressure. However, for silty-clay soils like A-4, A-6, and A-7-6 there was a general trend of decrease in M_R with increase in nominal maximum axial stress at the same level of confining pressure. Figures 17 through 32 show that generally, there is an increase in M_R with the increase in confining pressure.

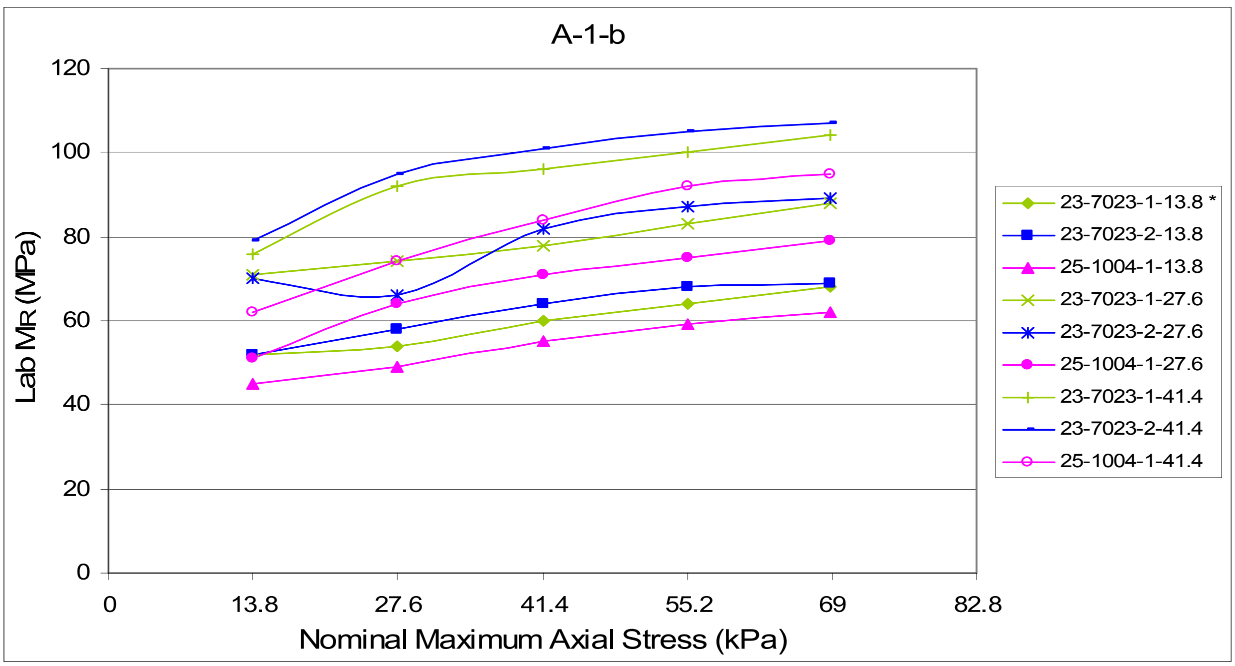


Figure 17. Nominal Maximum Axial Stress vs. M_R for A-1-b soils in New England at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

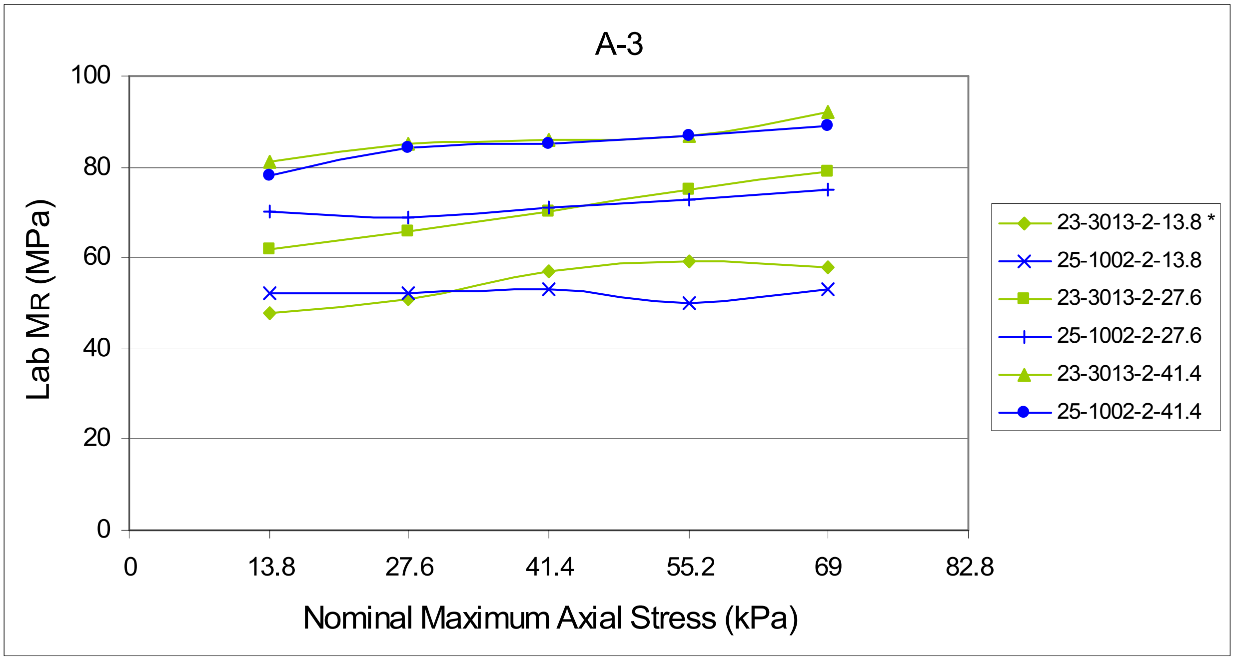


Figure 18. Nominal Maximum Axial Stress vs. M_R for A-3 soils in New England at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

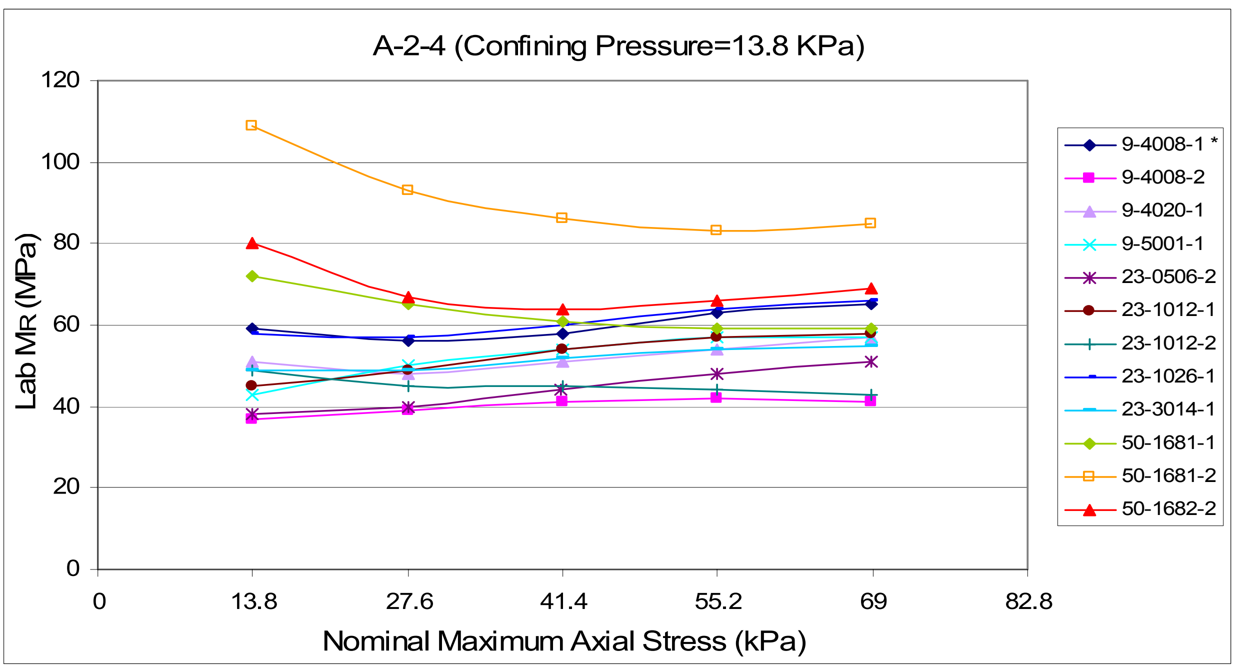


Figure 19. Nominal Maximum Axial Stress vs. M_R for A-2-4 soils in New England at Confining Pressure of 13.8 kPa (* State Code-SHRP ID-Test No.)

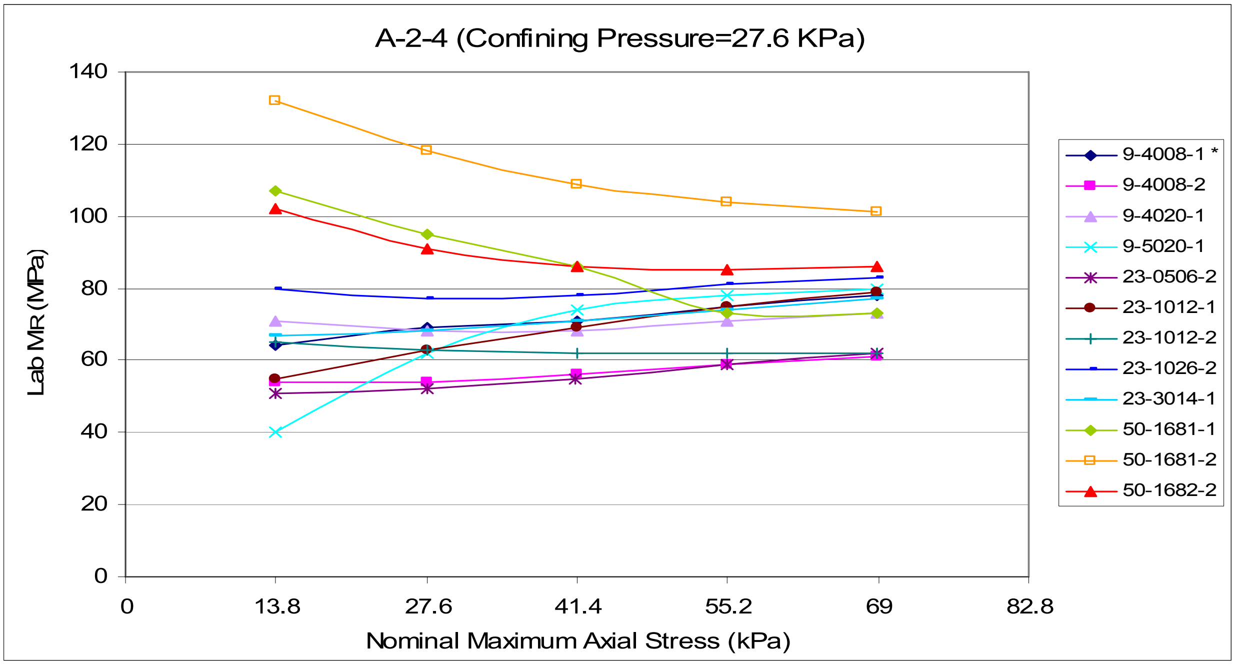


Figure 20. Nominal Maximum Axial Stress vs. M_R for A-2-4 soils in New England at Confining Pressure of 27.6 kPa (* State Code-SHRP ID-Test No.)

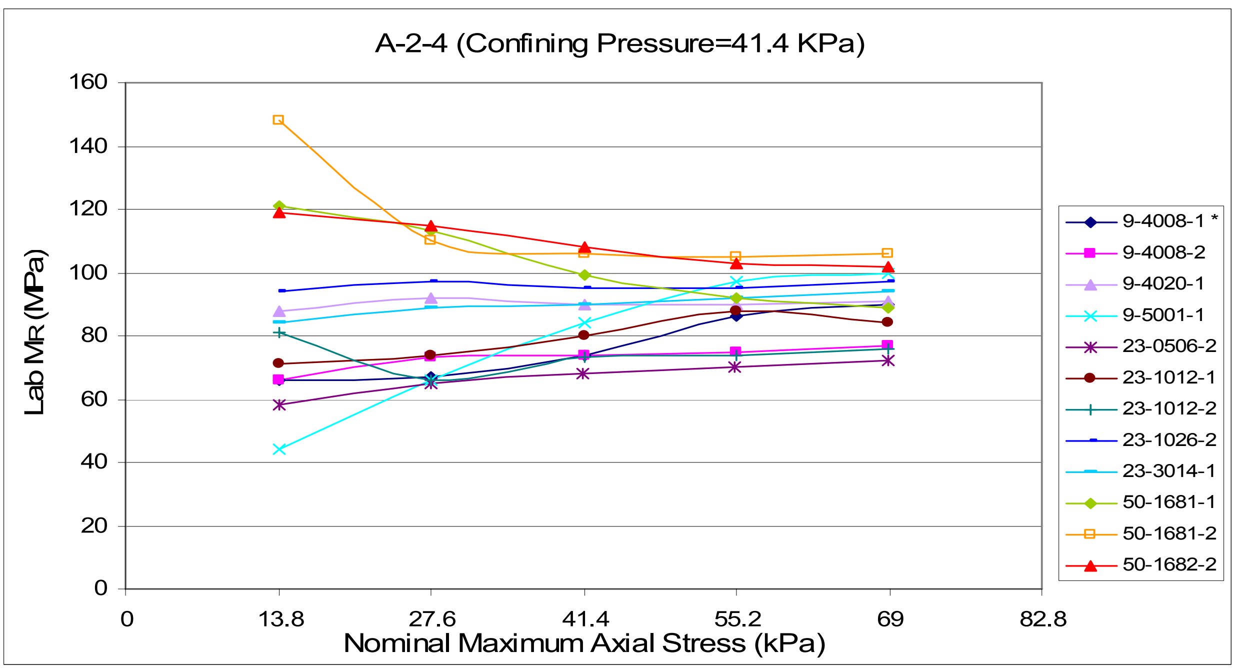


Figure 21. Nominal Maximum Axial Stress vs. M_R for A-2-4 soils in New England at Confining Pressure of 41.4 kPa (* State Code-SHRP ID-Test No.)

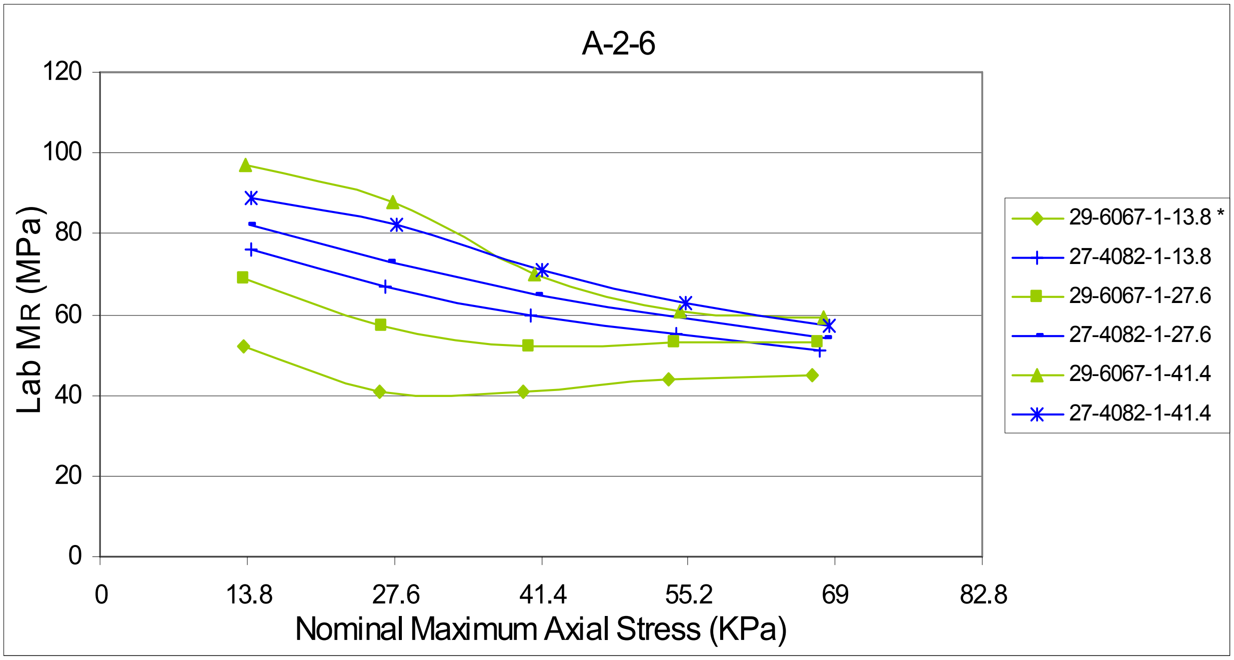


Figure 22. Nominal Maximum Axial Stress vs. M_R for A-2-6 soils at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

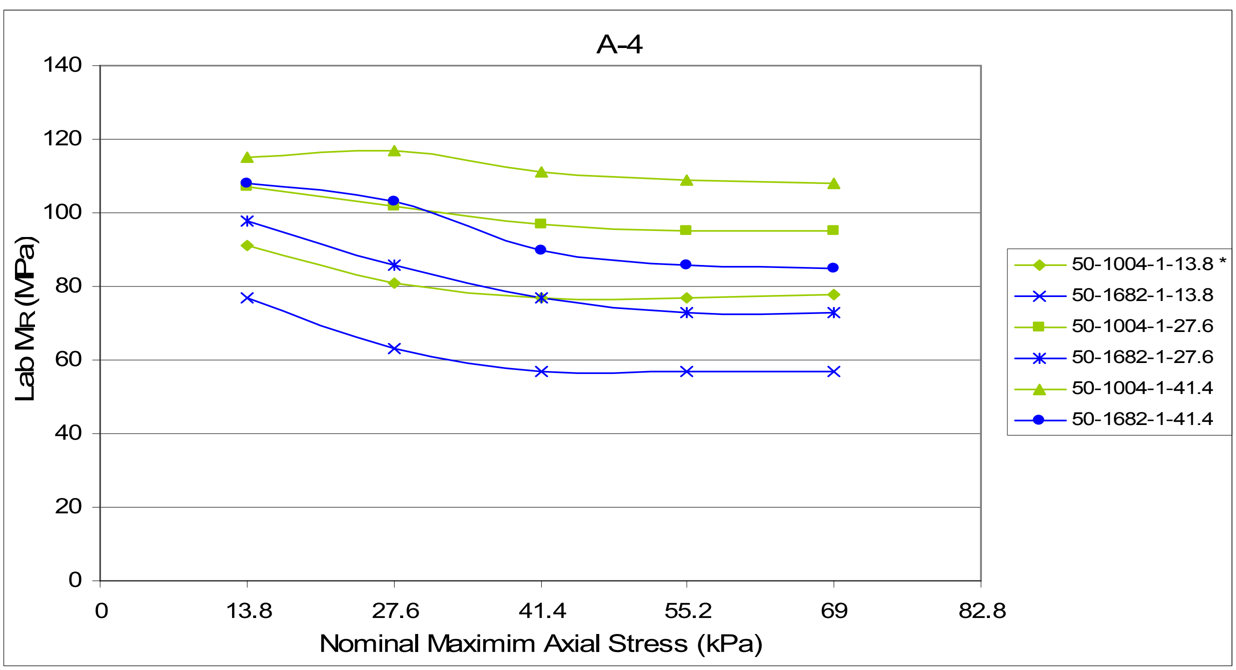


Figure 23. Nominal Maximum Axial Stress vs. M_R for A-4 soils in New England at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

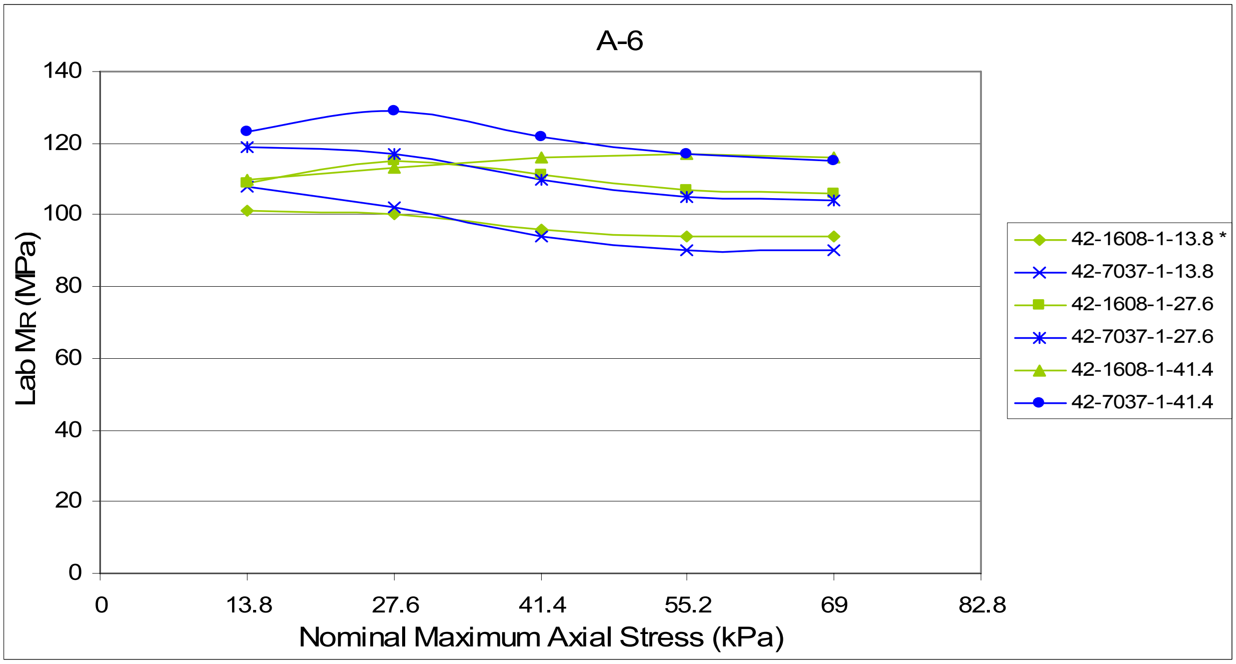


Figure 24. Nominal Maximum Axial Stress vs. M_R for A-6 soils at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

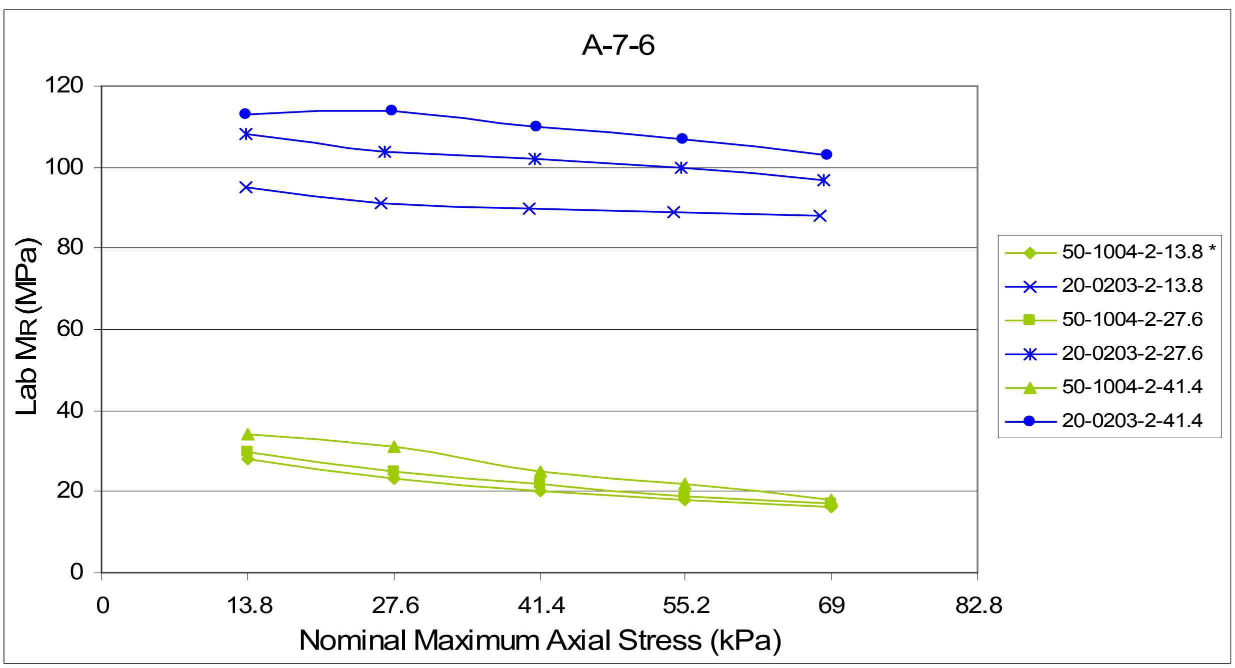


Figure 25. Nominal Maximum Axial Stress vs. M_R for A-7-6 soils at 3 levels of Confining Pressure (* State Code-SHRP ID-Test No.-Confining Pressure in kPa)

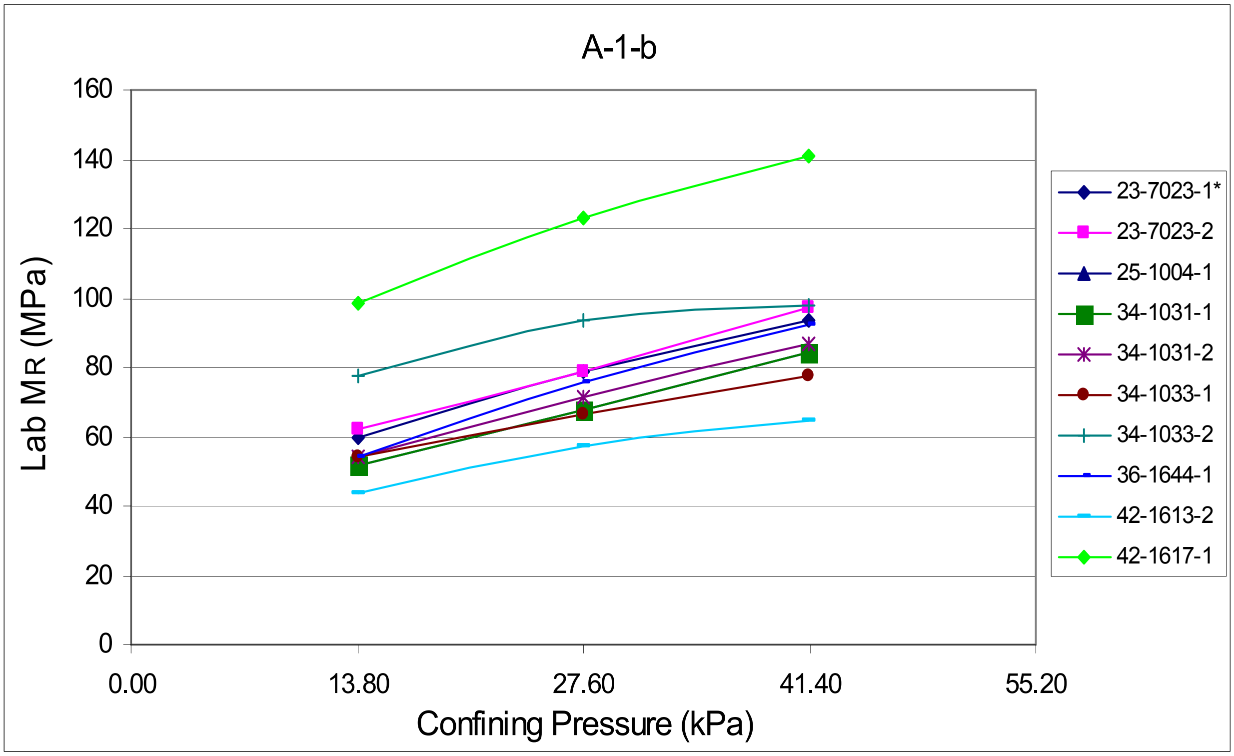


Figure 26. Confining Pressure vs. M_R for A-1-b soils (*State Code – SHRP ID – Test No.)

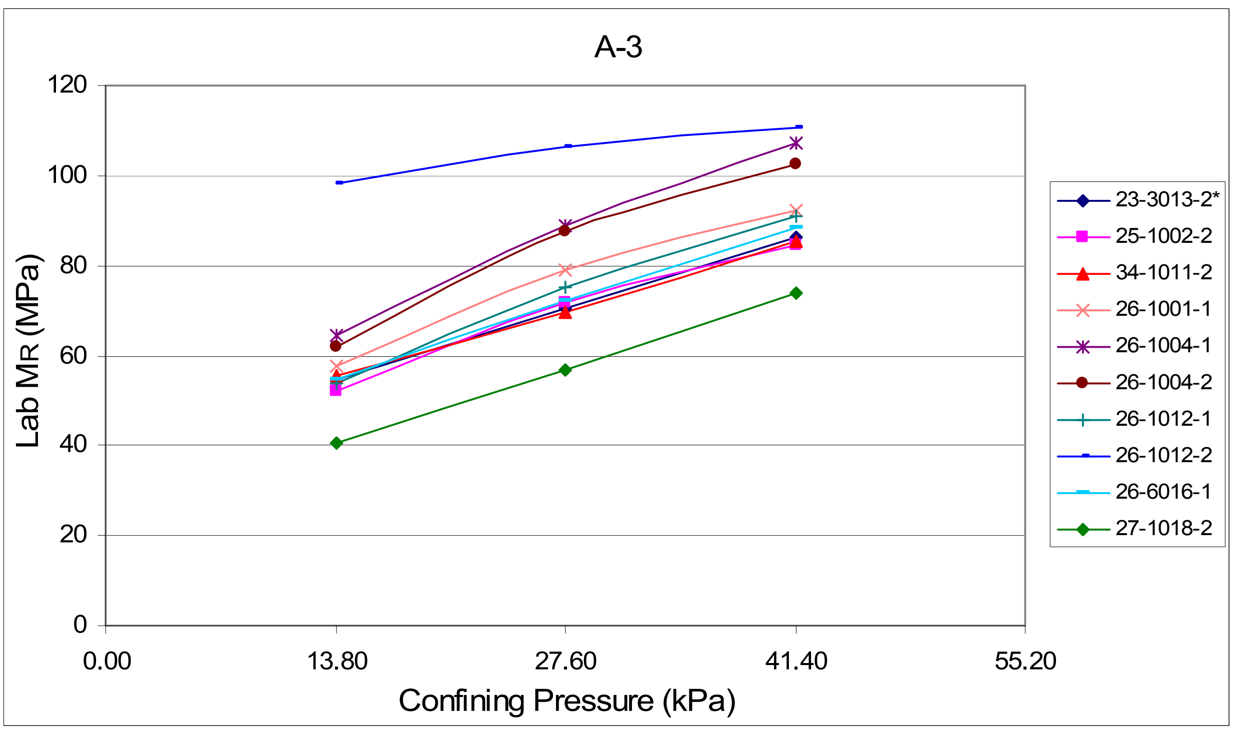


Figure 27. Confining Pressure vs. M_R for A-3 soils (*State Code – SHRP ID – Test No.)

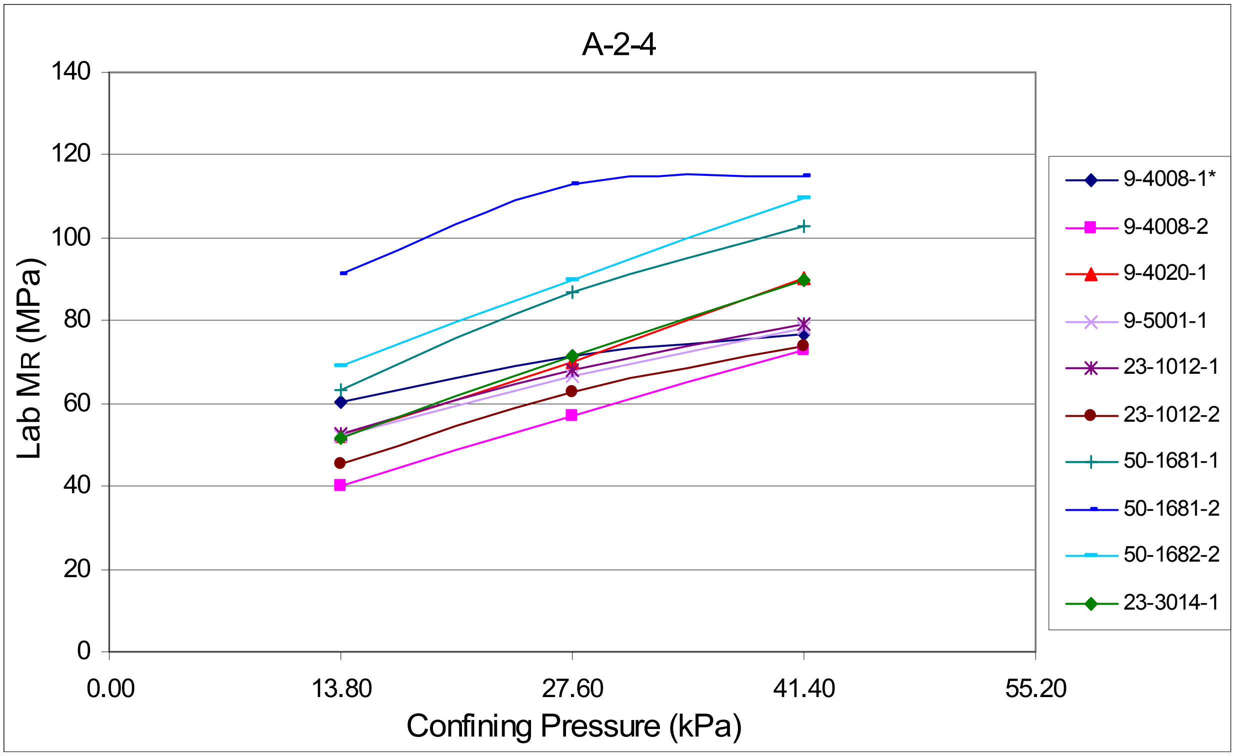


Figure 28. Confining Pressure vs. M_R for A-2-4 soils (*State Code – SHRP ID – Test No.)

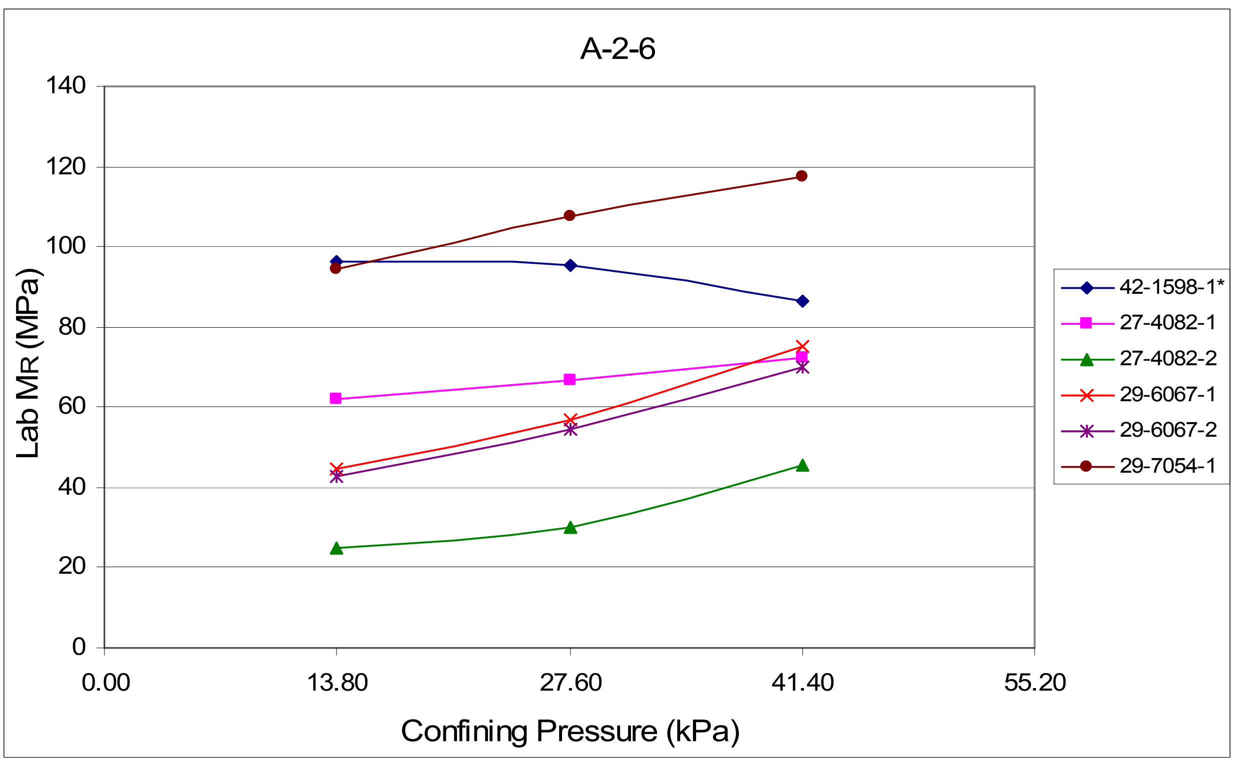


Figure 29. Confining Pressure vs. M_R for A-2-6 soils (*State Code – SHRP ID – Test No.)

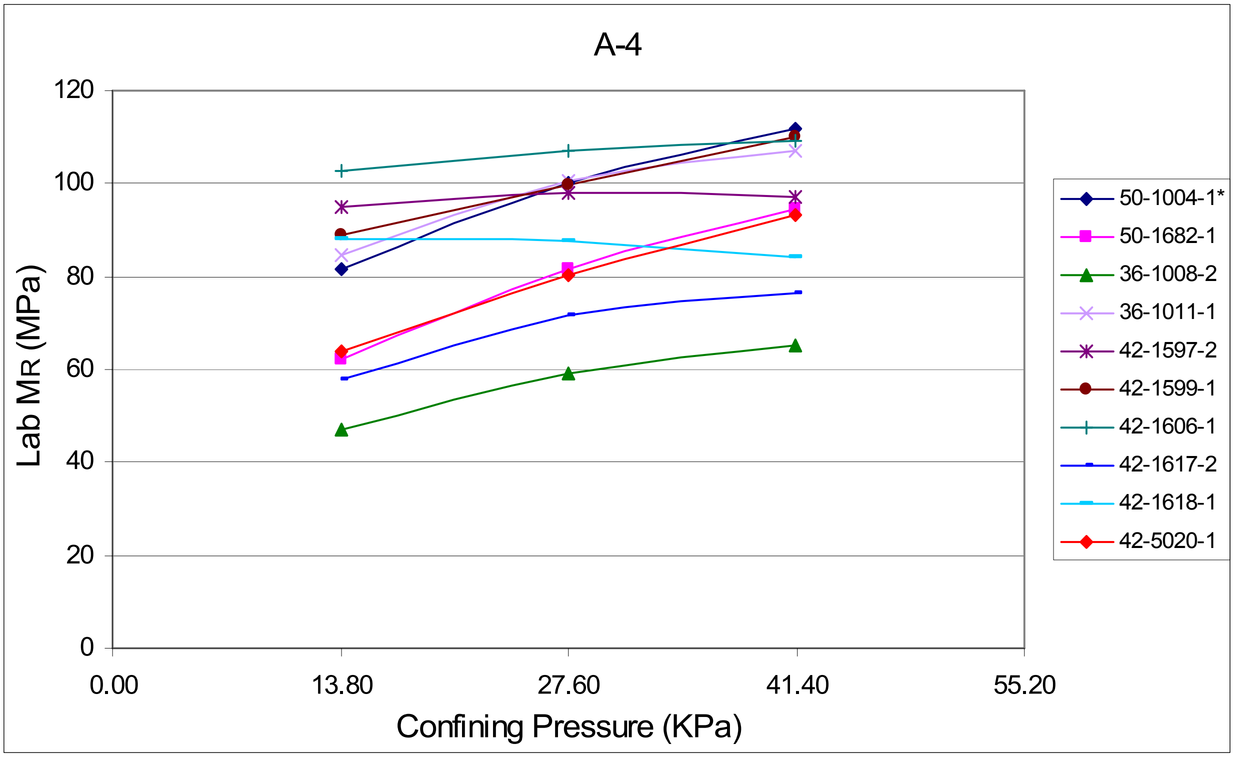


Figure 30. Confining Pressure vs. M_R for A-4 soils (*State Code – SHRP ID – Test No.)

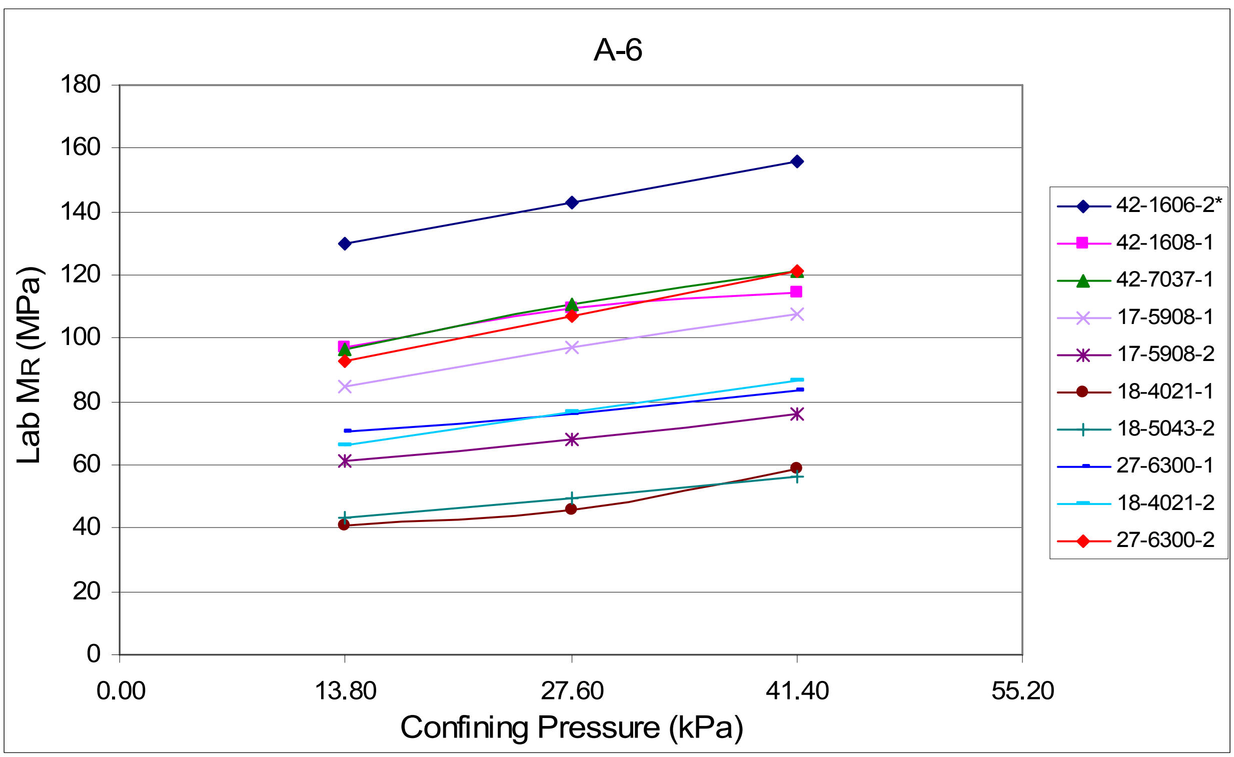


Figure 31. Confining Pressure vs. M_R for A-6 soils (*State Code – SHRP ID – Test No.)

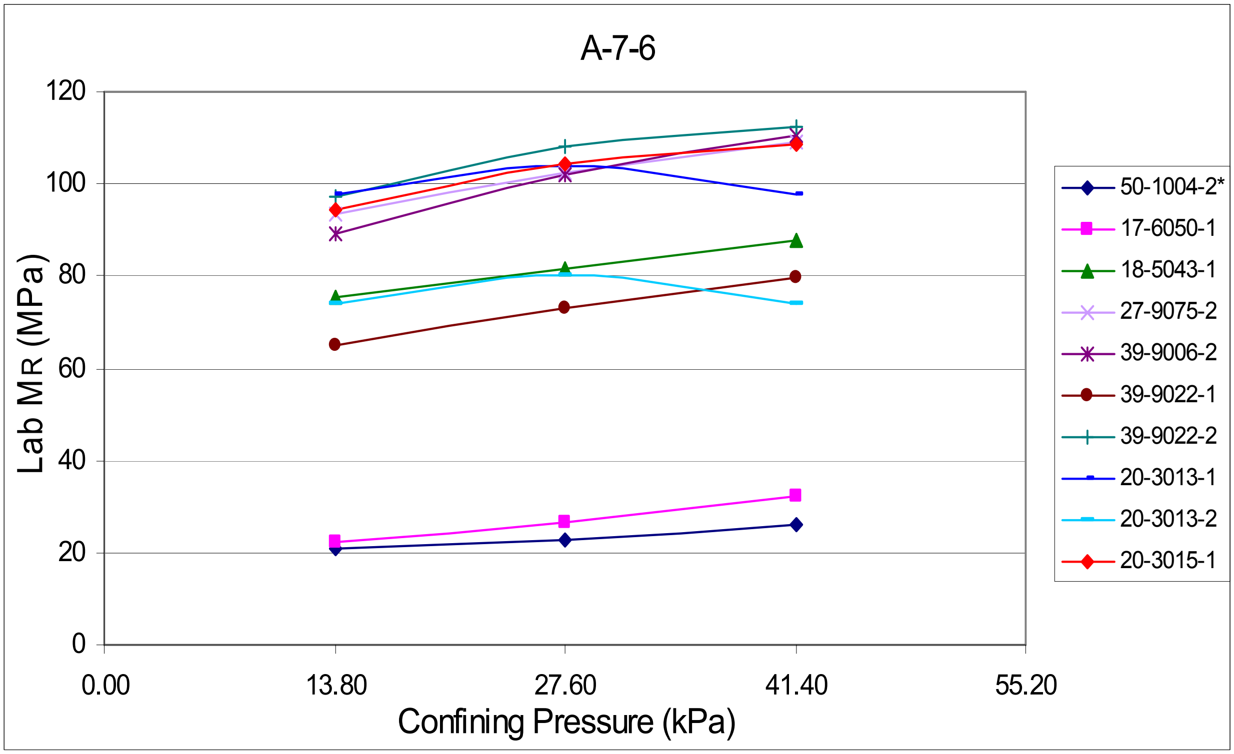


Figure 32. Confining Pressure vs. M_R for A-7-6 soils (*State Code – SHRP ID – Test No.)

4.3 Resilient Modulus Prediction Models

The determination of M_R using the repeated load triaxial test is a very sophisticated process that requires substantial time and resources. Therefore, most of the State Highway agencies prefer not to measure M_R in the laboratory frequently. Nondestructive deflection testing devices like the Falling Weight Deflectometer can also be used to measure the insitu modulus of the subgrade soil using backcalculation process. But from the studies so far, a definite relationship between the laboratory and backcalculated modulus value has not been established. Estimation of M_R from physical properties has been studied by several investigators in the past because tests for determining the physical properties are much simpler and cheaper than the test for direct evaluation of M_R itself. Moreover, the correlation of M_R with the physical properties allows the study of the seasonal effect on the value of M_R. Some of the studies that have developed prediction models for estimating the value of M_R from a set of physical properties and applied stresses during repeated load test include Santha (1994), Von Quintus and Killingsworth (1998) Mohammad et al (1999), and Yau and Von Quintus (2002).

Prediction models for estimating M_R values have been developed in this study for AASHTO soil types A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6. Prediction model for soil type A-2-6 could not be developed due to only small number of samples being available under this type. Only the reconstituted/disturbed test specimen test results have been used in developing these prediction models. Yau and Von Quintus (2002) have noted that sampling technique (disturbed/ undisturbed test specimens) of subgrade soils has an effect on the M_R test results for all soil groups (gravel, silt, clay) except sand. Von Quintus and Killingsworth (1998) observed significant improvement in correlation between M_R and soil physical properties when disturbed and undisturbed samples were separated for model prediction. Hence in this study we have considered only the reconstituted specimens. Prediction models for undisturbed soil specimens have not been developed because very little data is available for each soil type.

Resilient modulus test results that have been identified as anomaly in the report "Study of LTPP Laboratory Resilient Modulus Test Data and Response Characteristics" (Yau and Von Quintus 2002) have not been included in this study. Numbers of total, reconstituted/disturbed, and undisturbed soil samples available for the 6 AASHTO soil types (A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6) are presented in Table 8. Disturbed/Reconstituted soil samples are those which have experienced structural disturbances during the sampling operation and are recompacted in the laboratory before M_R test while undisturbed samples are those in which structural disturbance is kept to a minimum during the sampling process and are tested as obtained from the test site.

Three prediction models have been developed for each AASHTO soil type. The first set of models is the composite model that has been developed from all reconstituted soil specimens (MODEL1), the second set of models is from only those samples that have been compacted at the optimum moisture content only during M_R testing (MODEL2) and the third model set of models have been developed from the samples that have been compacted at insitu moisture content (MODEL3). Total of 259 test specimens have been included: 34 samples for A-1-b soils, 24 samples for A-3 soils, 52 samples for A-2-4 soils, 84 samples for A-4 soils, 40 samples for A-6 samples and 25 samples of A-7-6 soils. Only the tests with Record Status "E" in the LTPP database have been entered in this study as only these tests have passed all levels of LTPP quality control checks (see Appendix I.4 for details on LTPP quality control checks)

Table 8. Number of samples by AASHTO soil types for which data was extracted from the LTPP database

Soil Type	Total samples	Disturbed/Reconstituted samples	Undisturbed Samples
A-1-b	34	34	-
A-3	25	24	1
A-2-4	52	52	-
A-4	94	84	10
A-6	55	40	15
A-7-6	33	25	8
Total	293	259	34

4.3.1 Generalized Constitutive Model

Several constitutive models have been developed in the past in order to describe the nonlinear behavior of M_R for subgrade soils. Some of these models consisted of bulk stress only for granular soils or deviator stress only for cohesive soils or both bulk stress and deviator stress called universal model (Smart and Humphrey, 1999). The 2002 Design Guide suggests the use of the following generalized constitutive model for estimation of M_R:

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} \quad \ldots\ldots (2)$$

where, M_R = Resilient modulus

Pa = Normalizing stress (atmospheric pressure)

k_1, k_2, k_3 = Regression coefficients

θ = Bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$ ………………. (3)

σ_1 = Major principal stress

σ_2 = Intermediate principal stress (= σ_3 for M_R test on cylindrical specimen)

σ_3 = Minor principal stress / Confining pressure

τ_{oct} = Octahedral shear stress

$$= \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2} \quad \text{……………. (4)}$$

According to the 2002 Design Guide either linear or nonlinear regression analysis may be used to fit the analytical prediction model to laboratory generated M_R test data. Coefficient k_1 is directly proportional to Young's modulus. Hence, it cannot have a negative value since M_R cannot be negative. k_2 should be positive since increasing the bulk stress should produce stiffening effect on the material which results in higher M_R. Hence, the exponent of bulk stress (θ) should be positive. Similarly, k_3 should be negative since increase of shear stress produces softening effect on the material which results in lower M_R. Therefore, the exponent of octahedral shear stress (τ_{oct}), k_3 should be negative.

4.3.2 Regression Analysis Methodology

Multiple linear regression technique was carried out to determine the value of coefficients k_1, k_2, and k_3 for each individual soil specimen. Computer software SAS® 9.1 (2002-2003) was used for conducting the regression analysis. Equation (2) was transformed to the following form by taking logarithm on both sides to carry out linear regression:

$$\log M_R = \log(k_1 P_a) + k_2 \log\left(\frac{\theta}{P_a}\right) + k_3 \log\left(\frac{\tau_{oct}}{P_a}\right) \quad \text{…………………………….. (5)}$$

Regression was carried out between laboratory measured M_R values and the corresponding values of bulk stress and octahedral shear stress to get values of k_1, k_2, and k_3 for each sample. In the LTPP testing each sample was tested at 5 levels of deviator stress (12.4, 24.8, 37.3, 49.7 and 62.0 kPa) for 3 levels of confining pressure (13.8, 27.6 and 41.4 kPa) resulting in 15 combinations of stresses for each sample. Example of laboratory resilient modulus test results for one A-2-4 soil sample in Connecticut has been presented in Table 9. The complete set of M_R test data for all samples considered in the current study can be found in Tables I.2.1 to I.2.4 in Appendix I available in accompanying CD. Here the cyclic stress applied during M_R test has been taken equal to the deviator stress (σ_d) as suggested by various researchers in the past (Smart and Humphrey 1999). Deviator stress is given by,

$\sigma_d = \sigma_1 - \sigma_3$ ……………………….. (6)

Here since, $\sigma_2 = \sigma_3$ and $\sigma_d = \sigma_1 - \sigma_3$, Eq. (4) reduces to

$$\tau_{oct} = \frac{\sqrt{2}\times\sigma_d}{3} \quad \text{…………………… (7)}$$

Table 9. Sample Laboratory M_R test data (one A-2-4 soil specimen from Connecticut)

SHRP ID	State Code	La-yer No.	Test No.	Loc_ No	Sample No.	Conf-ining Pres-sure kPa	Nom_ Max_ Axial_ Stress kPa	MR_ Matl_ Type	Appl. Cyclic Load Avg. N	Appl. Cyclic Stress Avg. kPa	Appl. Contact Stress Avg. kPa	Resilient Strain Average	Resilient Modulus Average MPa
4008	9	1	2	BA*	BS**	13.8	13.8	2	51.3	12.9	1.4	0.000349	37
4008	9	1	2	BA*	BS**	13.8	27.6	2	102	25.8	2.8	0.000667	39
4008	9	1	2	BA*	BS**	13.8	41.4	2	152	38.4	4.1	0.000929	41
4008	9	1	2	BA*	BS**	13.8	55.2	2	200	50.5	5.5	0.001192	42
4008	9	1	2	BA*	BS**	13.8	68.9	2	247	62.2	6.9	0.001535	41
4008	9	1	2	BA*	BS**	27.6	13.8	2	51.9	13	1.4	0.000244	54
4008	9	1	2	BA*	BS**	27.6	27.6	2	102	25.8	2.8	0.000479	54
4008	9	1	2	BA*	BS**	27.6	41.4	2	153	38.5	4.1	0.000686	56
4008	9	1	2	BA*	BS**	27.6	55.2	2	202	51	5.5	0.000866	59
4008	9	1	2	BA*	BS**	27.6	68.9	2	251	63.4	6.9	0.001034	61
4008	9	1	2	BA*	BS**	41.4	13.8	2	51.5	13	1.4	0.000195	66
4008	9	1	2	BA*	BS**	41.4	27.6	2	102	25.7	2.8	0.000351	73
4008	9	1	2	BA*	BS**	41.4	41.4	2	152	38.3	4.1	0.000518	74
4008	9	1	2	BA*	BS**	41.4	55.2	2	201	50.8	5.5	0.000676	75
4008	9	1	2	BA*	BS**	41.4	68.9	2	252	63.5	6.9	0.000829	77

The values of various stresses and M_R used in Eq. (5) for each of the 15 combinations of stresses for each soil sample in the first step regression analysis are presented in Tables C.1 to C.6 in Appendix C. Since the applied cyclic stress or deviator stress (σ_d) and the confining pressure (σ_3) are known (measured), the major principal stress (σ_1) is computed from Eqn. (6). Thereafter, the bulk stress (θ) is computed using Eq. (3). The octahedral shear stress (τ_{oct}) is computed using Eq. (7). For an example, stresses (θ, and τ_{oct}) and M_R values used in the first step regression for one A-2-4 soil sample in Connecticut has been presented in Table 10.

Table 10. Sample stress and M_R values used in First Step Regression

State Code	SHRP ID	TN	Confining Pressure, σ_3 (kPa)	Deviator (Applied Cyclic) Stress, $\sigma_d = \sigma_1 - \sigma_3$ (kPa)	Resilient Modulus, M_R (MPa)	Bulk Stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3$ (kPa)	Octahedral Stress, τ_{oct} (kPa)	$\log(M_R)$	$\log(\theta_1/Pa)$	$\log(\tau_{oct}/Pa)$
9	4008	2	13.8	12.9	37	54.3	6.081	1.568	-0.271	-1.222
9	4008	2	13.8	25.8	39	67.2	12.162	1.591	-0.178	-0.921
9	4008	2	13.8	38.4	41	79.8	18.102	1.613	-0.103	-0.747
9	4008	2	13.8	50.5	42	91.9	23.806	1.623	-0.042	-0.629
9	4008	2	13.8	62.2	41	103.6	29.321	1.613	0.009	-0.539
9	4008	2	27.6	13	54	95.8	6.128	1.732	-0.025	-1.222
9	4008	2	27.6	25.8	54	108.6	12.162	1.732	0.03	-0.921
9	4008	2	27.6	38.5	56	121.3	18.149	1.748	0.078	-0.747
9	4008	2	27.6	51	59	133.8	24.041	1.771	0.121	-0.625
9	4008	2	27.6	63.4	61	146.2	29.887	1.785	0.159	-0.53
9	4008	2	41.4	13	66	137.2	6.128	1.82	0.132	-1.222
9	4008	2	41.4	25.7	73	149.9	12.115	1.863	0.17	-0.921
9	4008	2	41.4	38.3	74	162.5	18.055	1.869	0.205	-0.75
9	4008	2	41.4	50.8	75	175	23.947	1.875	0.237	-0.627
9	4008	2	41.4	63.5	77	187.7	29.934	1.886	0.268	-0.53

It must be noted here that since the applied cyclic/deviator stress (σ_d) during the tests is nearly the same from one sample to another and so is σ_3, the values of σ_1, θ, and τ_{oct} calculated are more or less the same for all the samples.

In this study, the unit used for M_R is MPa and for values of stresses (θ, τ_{oct}, and P_a) appearing on the right side of Eq. (2) is kPa. The value of atmospheric pressure (P_a) used in this study is 101.325 kPa which is the standard atmospheric pressure at sea level. List of k values and the corresponding R^2 values obtained after regression for each sample has been reported in Tables D.1 to D.6, Appendix D for soil types A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6 respectively.

After obtaining k_1, k_2, and k_3 for each soil sample, a second set of regression was carried out to relate these k values with the physical properties of soil for the 6 types of subgrade soils, AASHTO A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6. The soil properties that were considered for the study are:

Specimen moisture content (MC)
Optimum moisture content (OMC)
Moisture content ratio (MCR=MC/OMC)
Specimen dry density (DD)
Maximum dry density (MAXDD)
Dry density ratio (DDR=DD/MAXDD)
Liquid limit (LL)
Plastic limit (PL)
Percent passing 3" sieve (S3)
Percent passing 2" sieve (S2)
Percent passing 1 1/2" sieve (S1_HALF)
Percent passing 1" sieve (S1)
Percent passing 3/4" sieve (S3_4)
Percent passing 1/2" sieve (S1_2)
Percent passing 3/8" sieve (S3_8)
Percent passing #4 sieve (SN4)
Percent passing #10 sieve (SN10)
Percent passing #40 sieve (SN40)
Percent passing #80 sieve (SN80)
Percent passing #200 sieve (SN200)
Percent coarse sand (CSAND, particles of size 2 – 0.42 mm)
Percent fine sand (FSAND, particles of size 0.42 - .074 mm)
Percent silt (SILT, particles of size 0.074 – 0.002 mm)
Percent clay (CLAY, particles of size 0.002 mm).

Soil samples that gave negative values for k_1 and k_2, or positive values for k_3 were not used in the second set regression for the reasons noted above in Section "Generalized Constitutive Model." The 2002 Design Guide suggests using the k-values from those individual samples that yield multiple correlation coefficient (R^2) equal to 0.9 or higher from the regression analysis of M_R using Eq. (5). Otherwise, consideration should be given to use different constitutive model for soil samples yielding R^2 less than 0.90. Therefore, in this study only the samples that resulted in R^2 equal to 0.90 or above from the regression analysis of M_R relation (Eq. (5)) were included in the overall regression for a particular soil type to develop models relating coefficients, k_1, k_2, and k_3, with the soil properties. The properties of each soil sample that were used in second step regression for each AASHTO soil type has been presented in Tables D.7 to D.12 in Appendix D.

The mean and range of k-coefficient (k_1, k_2, and k_3) values obtained for the individual soil specimens from the regression analysis of Eq. (5) that were used in the second set regression analysis of all reconstituted samples for the 6 different AASHTO soil types have been presented in Table 11 below. Similar data for the models containing only those samples compacted at optimum moisture content or only the samples compacted at insitu moisture content only have been presented in Tables 12 and 13. The values of k coefficients obtained for individual soil sample have been presented in Tables D.1 to D.6 in Appendix D.

Table 11. Range of k coefficients for all reconstituted samples used in second step regression

AASHTO Soil Type	Variable	No. of Samples	Mean	Standard Deviation	Minimum	Maximum
A-1-b	k_1	29	0.5077	0.1243	0.2817	1.0142
	k_2	29	0.6863	0.0985	0.4689	0.8493
	k_3	29	-0.1426	0.0703	-0.3579	-0.0089
A-3	k_1	19	0.5019	0.0575	0.3697	0.5834
	k_2	19	0.6675	0.0676	0.5681	0.8219
	k_3	19	-0.1097	0.0252	-0.1493	-0.0545
A-2-4	k_1	40	0.4198	0.0895	0.2163	0.6685
	k_2	40	0.6295	0.1426	0.2857	0.8830
	k_3	40	-0.2005	0.0853	-0.4150	-0.0845
A-4	k_1	66	0.4398	0.2295	0.1293	1.2192
	k_2	66	0.4462	0.1579	0.1696	0.9885
	k_3	66	-0.2871	0.1033	-0.5701	-0.0902
A-6	k_1	36	0.5116	0.3569	0.1202	1.5382
	k_2	36	0.3016	0.1280	0.1742	0.8854
	k_3	36	-0.3028	0.1535	-0.6281	-0.0390
A-7-6	k_1	20	0.5244	0.2735	0.0664	1.0578
	k_2	20	0.2309	0.0793	0.1305	0.4707
	k_3	20	-0.2399	0.1551	-0.6198	-0.0924

Table 12. Range of k coefficients for samples compacted at optimum moisture content used in second step regression

AASHTO Soil Type	Variable	No. of Samples	Mean	Standard Deviation	Minimum	Maximum
A-1-b	k_1	10	0.5136	0.0781	0.4361	0.6830
	k_2	10	0.7113	0.0721	0.5991	0.8145
	k_3	10	-0.1222	0.0671	-0.2541	-0.0089
A-3	k_1	14	0.5029	0.0559	0.3697	0.5834
	k_2	14	0.6600	0.0611	0.5681	0.7498
	k_3	14	-0.1104	0.0285	-0.1493	-0.0545
A-2-4	k_1	28	0.4329	0.0899	0.2163	0.6685
	k_2	28	0.6217	0.1431	0.2857	0.8830
	k_3	28	-0.2019	0.0916	0.4150	-0.0845
A-4	k_1	41	0.4896	0.2349	0.1663	1.2192
	k_2	41	0.4115	0.1233	0.1696	0.6666
	k_3	41	-0.2882	0.1011	-0.5701	-0.1043
A-6	k_1	23	0.5194	0.3171	0.1202	1.2086
	k_2	23	0.2896	0.0796	0.1844	0.5693
	k_3	23	-0.3057	0.1694	-0.6281	-0.0390
A-7-6	k_1	13	0.5935	0.1964	0.2491	0.9793
	k_2	13	0.2181	0.0584	0.1488	0.3660
	k_3	13	-0.1920	0.0759	-0.3428	-0.0946

Table 13. Range of k coefficients for samples compacted at insitu moisture content used in second step regression

AASHTO Soil Type	Variable	No. of Samples	Mean	Standard Deviation	Minimum	Maximum
A-1-b	k_1	19	0.5046	0.1448	0.2817	1.0142
	k_2	19	0.6732	0.1094	0.4689	0.8493
	k_3	19	-0.1534	0.0712	-0.3579	-0.0696
A-3	k_1	4	0.4844	0.0702	0.3965	0.5639
	k_2	4	0.7083	0.0872	0.6259	0.8218
	k_3	4	-0.1065	0.0168	-0.1180	-0.0821
A-2-4	k_1	12	0.3892	0.0843	0.2531	0.5044
	k_2	12	0.6478	0.1461	0.3306	0.8759
	k_3	12	-0.1972	0.0718	-0.3278	-0.0904
A-4	k_1	25	0.3582	0.1989	0.1293	0.9789
	k_2	25	0.5031	0.1916	0.2552	0.9885
	k_3	25	-0.2853	0.1089	-0.5348	-0.0902
A-6	k_1	13	0.4978	0.4323	0.1428	1.5382
	k_2	13	0.3228	0.1881	0.1742	0.8854
	k_3	13	-0.2977	0.1270	-0.4939	-0.0941
A-7-6	k_1	8	0.4823	0.4135	0.0664	1.0849
	k_2	8	0.2602	0.1027	0.1305	0.4707
	k_3	8	-0.3007	0.2227	-0.6198	-0.0924

In the second set of regression analysis, a list of models was first printed using RSQUARE selection method available in SAS® (2002-2003). The RSQUARE method gives several subsets of independent variables that best predict a dependent variable by linear regression in the given sample (SAS® 9.1.3, 2002-2003). A sample partial output of RSQUARE selection method for the k_3 coefficient of A-2-4 soil (all reconstituted samples included) has been presented in Table 14. From this set of models, a model which had higher value of R^2, with the Variance Inflation Factor (VIF) for the variables less than 10 was selected. As a rule of thumb, variables with VIF greater than 10 are to be investigated to check for multicollinearity (Chen et al 2004). Chatterjee and Price (1977) have mentioned that VIF in excess of 10 is an indication that multicollinearity may cause problems in estimation. Besides R^2, adjusted (adj.) R^2 value was also examined while selecting a model. Ordinary R^2 value always increases (at least not decrease) as more number of predictor variables are added to the model even if the variables are not related significantly to the variable to be predicted (Montgomery and Peck 1992). But the adjusted R^2 can decrease if unnecessary terms are added. The adjusted R^2 value gives a more honest estimation of R^2 (Chen et al 2004) and guards against addition of unnecessary terms. Therefore, a model which had higher adjusted R^2 besides having high R^2 was selected. Furthermore, while choosing the final model, a model that contains several relevant soil property predictors like moisture content, density, and gradation were preferred over a model having all gradation variables although it had higher R^2. All the regression equations developed were checked to see if they satisfied the assumptions of linear regression like normality of residuals, homogeneity of variance. A sample partial output of the result of second step regression analysis for the k_3 coefficient of A-2-4 soil (all reconstituted samples included) has been presented in Table 15.

Table 14. Partial output of RSQUARE selection method for the k_3 coefficient of A-2-4 soil (all reconstituted samples)

Number in Model	R-Square	Variables in Model
6	0.6804	OMC LL S2 SN10 FSAND CLAY
6	0.6771	MC DDR LL S2 SN10 CLAY
6	0.6767	OMC LL S2 SN4 FSAND CLAY
6	0.6766	OMC LL S1_HALF SN10 FSAND CLAY
6	0.6765	OMC LL S3_4 SN4 FSAND CLAY
6	0.6756	OMC LL S3_4 SN10 FSAND CLAY
6	0.6746	OMC LL S2 SN10 SN40 SILT
7	0.7146	OMC DD MaxDD DDR LL S2 FSAND
7	0.7146	OMC DD MaxDD DDR LL S3 FSAND
7	0.7115	OMC DD MaxDD DDR LL S1_HALF FSAND
7	0.7095	OMC DD MaxDD DDR LL S2 SN10
7	0.7087	OMC DD MaxDD DDR LL S3 SN10
7	0.7083	OMC DD MaxDD DDR LL S2 S1_2
7	0.7077	OMC DD MaxDD DDR LL S2 SN4
7	0.7066	OMC DD MaxDD DDR LL S2 S3_8
7	0.7063	OMC DD MaxDD DDR LL S3 SN4
7	0.7059	OMC DD MaxDD DDR LL S1_HALF SN10
7	0.7048	OMC DD MaxDD DDR LL S1 FSAND
7	0.7047	OMC DD MaxDD DDR LL S1_HALF SN4
7	0.7040	OMC DD MaxDD DDR LL S1_HALF S1_2
7	0.7033	OMC DD MaxDD DDR LL S1_HALF S3_8
7	0.7029	OMC DD MaxDD DDR LL S3_4 S1_2
7	0.7022	OMC DD MaxDD DDR LL S3 S3_8
7	0.7011	OMC DD MaxDD DDR LL S3 S1_2
7	0.7004	OMC DD MaxDD DDR LL S2 S3_4
7	0.7002	OMC DD MaxDD DDR LL S3 SN40
7	0.6996	OMC DD MaxDD DDR LL S2 SN40
7	0.6993	OMC DD MaxDD DDR PL S3 FSAND
7	0.6992	OMC DD MaxDD DDR LL S1 SN10
7	0.6988	OMC DD MaxDD DDR LL S1 SN4
7	0.6983	MC OMC DD MaxDD DDR LL FSAND
7	0.6982	OMC MCR DD MaxDD DDR LL FSAND
7	0.6979	OMC DD MaxDD DDR LL S3_4 SN4
7	0.6978	OMC DD MaxDD DDR LL S3_4 S3_8
7	0.6978	OMC DD MaxDD DDR LL S3_4 FSAND
7	0.6973	OMC DD MaxDD DDR LL S1 S1_2
7	0.6969	OMC DD MaxDD DDR LL S3_4 SN10
7	0.6958	OMC DD MaxDD DDR LL S1 S3_8
7	0.6939	OMC DD MaxDD DDR LL S1_HALF SN40
7	0.6935	OMC MCR DD MaxDD DDR LL SN40
7	0.6933	OMC MCR LL S2 SN40 SN80 CLAY --->>> SELECTED MODEL
7	0.6931	MC OMC LL S2 SN10 FSAND CLAY
7	0.6929	OMC DD MaxDD DDR PL S3 S3_8
8	0.7370	MC OMC DD MaxDD DDR LL S3 SN10
8	0.7362	MC MCR DD MaxDD DDR LL S2 SN10
8	0.7361	MC OMC DD MaxDD DDR LL S2 SN10
8	0.7359	MC OMC DD MaxDD DDR LL S2 S1_2
8	0.7359	MC MCR DD MaxDD DDR LL S3 SN10
8	0.7354	MC OMC DD MaxDD DDR LL S3 SN4
8	0.7350	MC MCR DD MaxDD DDR LL S2 SN4

Table 15. Partial output of regression for the model selected for the k_3 coefficient of A-2-4 soil (all reconstituted samples)

```
                              The REG Procedure
                               Model: MODEL1
                         Dependent Variable: K3 K3


                   Number of Observations Read          40
                   Number of Observations Used          40


                            Analysis of Variance

                                   Sum of           Mean
      Source               DF        Squares         Square    F Value    Pr > F

      Model                 7        0.19669        0.02810      10.33    <.0001
      Error                32        0.08700        0.00272
      Corrected Total      39        0.28369


                Root MSE              0.05214    R-Square     0.6933
                Dependent Mean       -0.20048    Adj R-Sq     0.6262
                Coeff Var           -26.00960


                            Parameter Estimates


                               Parameter      Standard                          Variance
Variable    Label       DF      Estimate         Error    t Value    Pr > |t|     Inflation

Intercept   Intercept    1       0.50825       0.21808       2.33      0.0262             0
OMC         OMC          1      -0.01956       0.00668      -2.93      0.0063       1.66150
MCR         MCR          1      -0.07234       0.05043      -1.43      0.1611       1.37691
LL          LL           1      -0.00492       0.00112      -4.39      0.0001       1.78767
S2          S2           1      -0.00652       0.00238      -2.74      0.0101       1.40659
SN40        SN40         1       0.00384    0.00082932       4.63      <.0001       2.55033
SN80        SN80         1      -0.00153    0.00084707      -1.80      0.0807       1.54006
CLAY        CLAY         1       0.00344       0.00235       1.47      0.1525       1.98084
```

4.3.3 Results of Regression Analysis

4.3.3.1 Soil Type: A-1-b

Thirty four test specimens from total of 13 states in the New England and nearby regions were initially analyzed to obtain the k coefficients (k_1, k_2, and k_3) for individual soil samples with the known laboratory M_R values using Eq. (5). Among these, 3 samples resulted in positive k_3 and 2 samples resulted in R^2 less than 0.90. These 5 samples were therefore not used for building the prediction models for k coefficients in the second step regression analysis that relates the k coefficients with the physical soil properties. Among the 29 samples that qualified for second step regression, 10 samples had been compacted at optimum moisture content and 19 samples had been compacted at insitu moisture content.

- **All reconstituted samples:**

The final regression equations for k_1, k_2, and k_3 obtained from the second step regression analysis for all 29 reconstituted samples are as given below.

$$\log k_1 = 0.09931 - 0.00743 \times MC + 0.00009293 \times DD + 0.00505 \times LL - 0.00466 \times S3\_8 - 0.01157 \times SN200 \quad (R^2 = 0.57;\ Adj.\ R^2 = 0.47) \quad (8)$$

$$k_2 = -0.86401 - 0.01884 \times OMC - 0.00116 \times DD + 2.01898 \times DDR + 0.02548 \times S1 - 0.00691 \times SN10 - 0.01047 \times SN80 + 0.03127 \times SILT \quad (R^2 = 0.68;\ Adj.\ R^2 = 0.58) \quad (9)$$

$$k_3 = -0.74756 - 0.00913 \times MC - 0.00041464 \times DD - 0.00472 \times PL + 0.03540 \times S3 - 0.02075 \times S2 \quad (R^2 = 0.55;\ Adj.\ R^2 = 0.46) \quad (10)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (8), (9), and (10) along with 95% confidence interval lines has been presented in Figures 33, 34, and 35. Numerical values of these predicted k coefficients can be found in Table D.13, Appendix D.

The predicted values of M_R can now be obtained by substituting available soil physical properties values in the right hand side of Eqs. (8), (9), and (10) to determine k_1, k_2, and k_3 respectively, and then using these predicted values of k coefficients into Eq. (5). The tabulated values of laboratory and predicted M_R values has been presented in Tables C.1, Appendix C. The plot for predicted M_R versus laboratory M_R has been shown in Figure 36. The analysis of laboratory and predicted M_R showed that 59.95 % of predicted M_R values were within ± 10% of the laboratory M_R values and 94.21 % of predicted M_R values were within ± 20% of the laboratory M_R values.

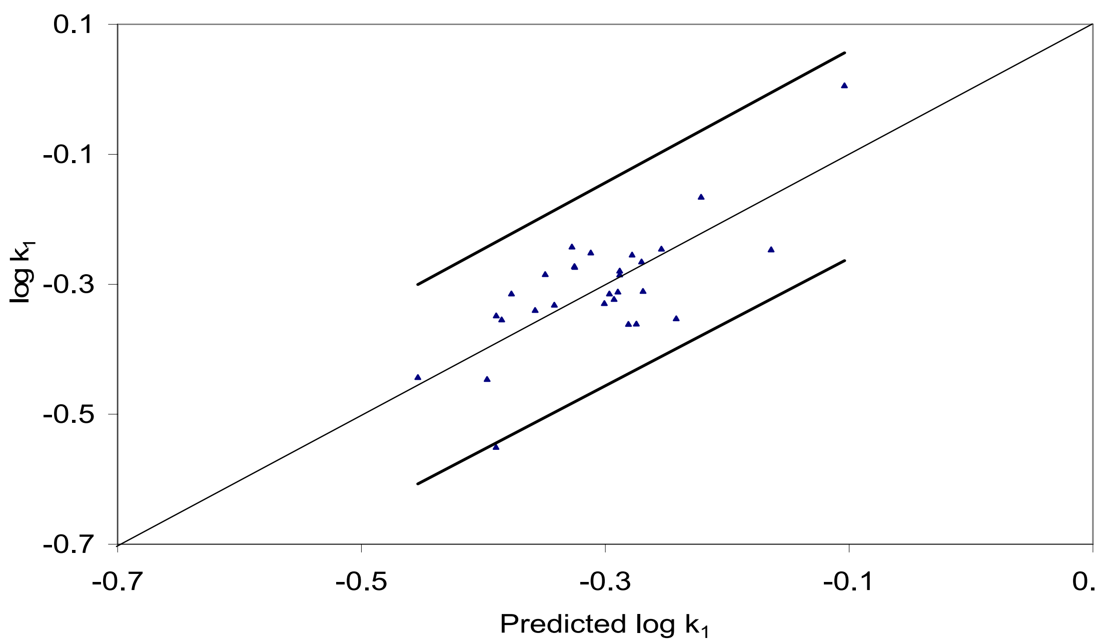


Figure 33. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-1-b soils

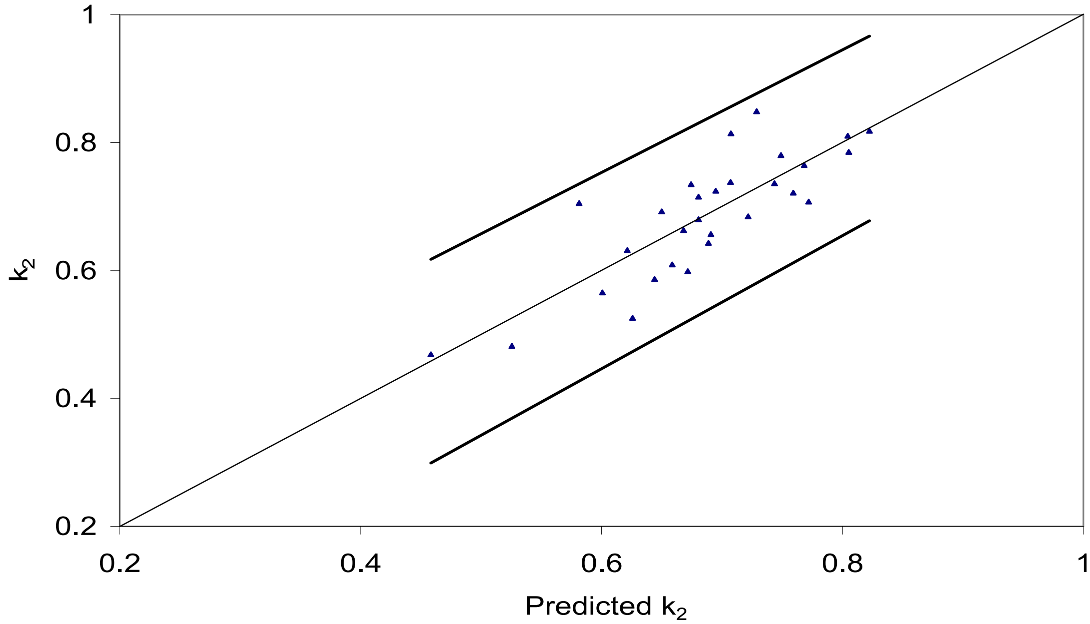


Figure 34. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-1-b soils

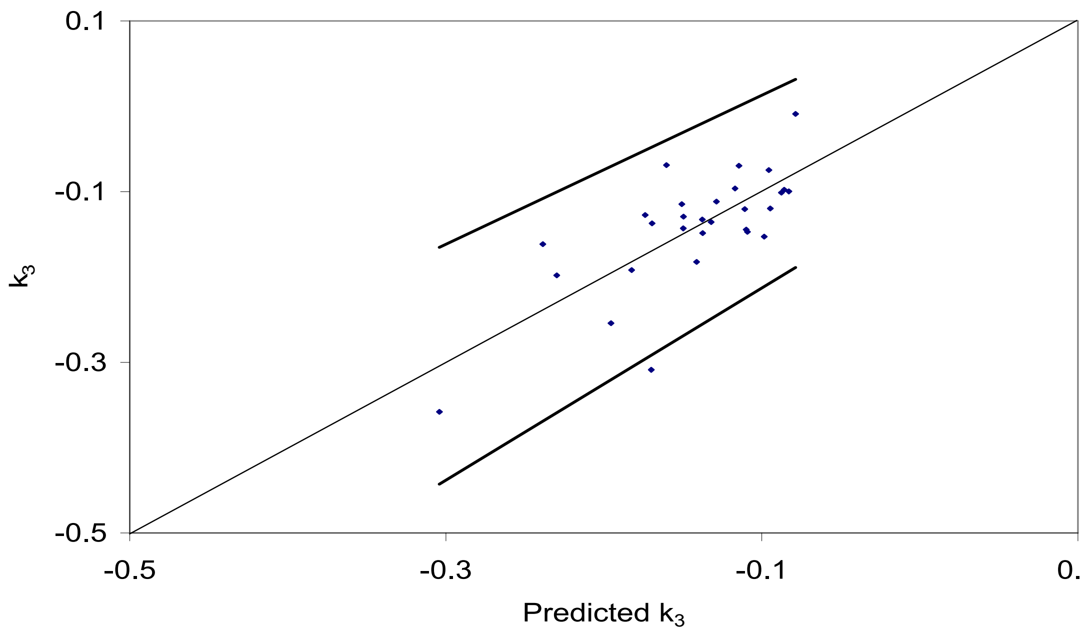


Figure 35. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-1-b soils

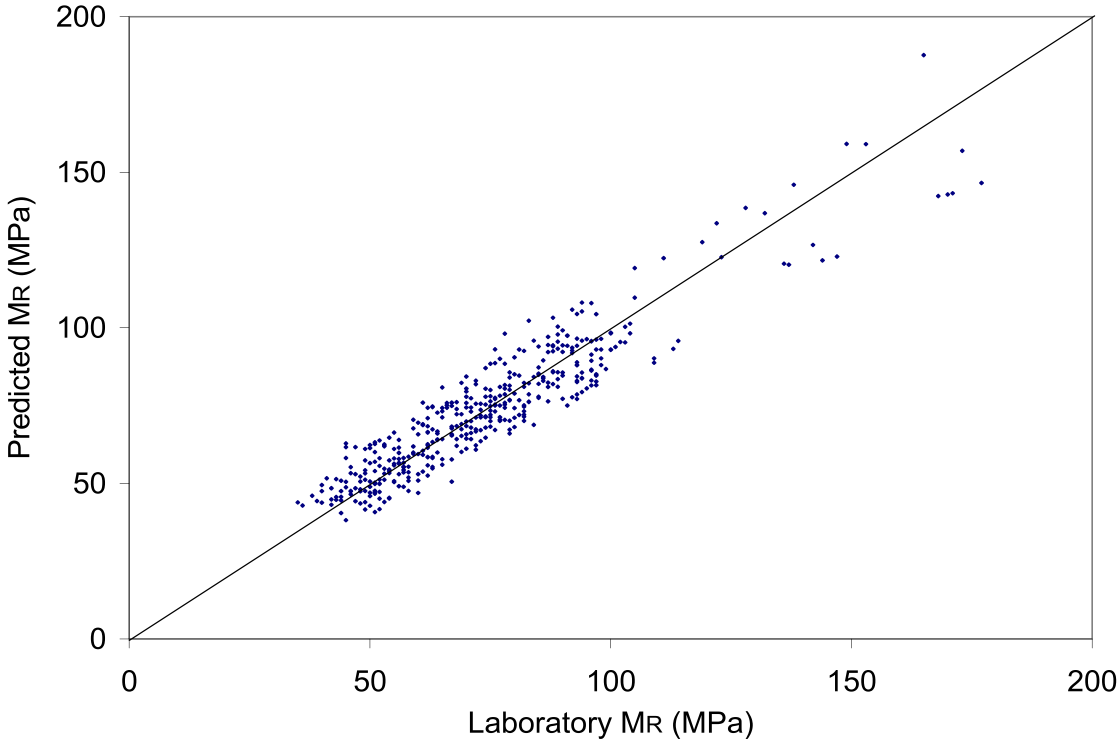


Figure 36. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-1-b soils

- **Samples compacted at optimum moisture content :**

Regression equations developed for the 10 A-1-b samples compacted at optimum moisture content are as follows:

$$\log k_1 = -9.85454 - 0.01714 \times OMC - 0.00078852 \times DD + 0.11588 \times S1\_HALF - 0.00616 \times SN10 + 0.00279 \times FSAND \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.97) \quad (11)$$

$$k_2 = -1.15403 + 0.03198 \times OMC + 5.69990 \times DDR - 0.04336 \times S1\_HALF + 0.01404 \times SN40 + 0.00476 \times CSAND - 0.00649 \times FSAND \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.98) \quad (12)$$

$$k_3 = 0.22460 - 0.02071 \times OMC - 0.00010179 \times MAXDD - 0.00046354 \times SN10 - 0.00682 \times SN40 + 0.00936 \times FSAND \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \quad (13)$$

The plot of predicted M_R calculated from the predicted values of k_1, k_2, and k_3 from Eqs. (11), (12), and (13) against laboratory measured M_R values has been presented in Figure 37 below. Numerical values of the predicted k coefficients can be found in Table D.13, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.1, Appendix C. The analysis of laboratory and predicted M_R showed that 96.00 % of predicted M_R values were within ± 10% of the laboratory M_R values and 98.00 % of predicted M_R values were within ± 20% of the laboratory M_R values.

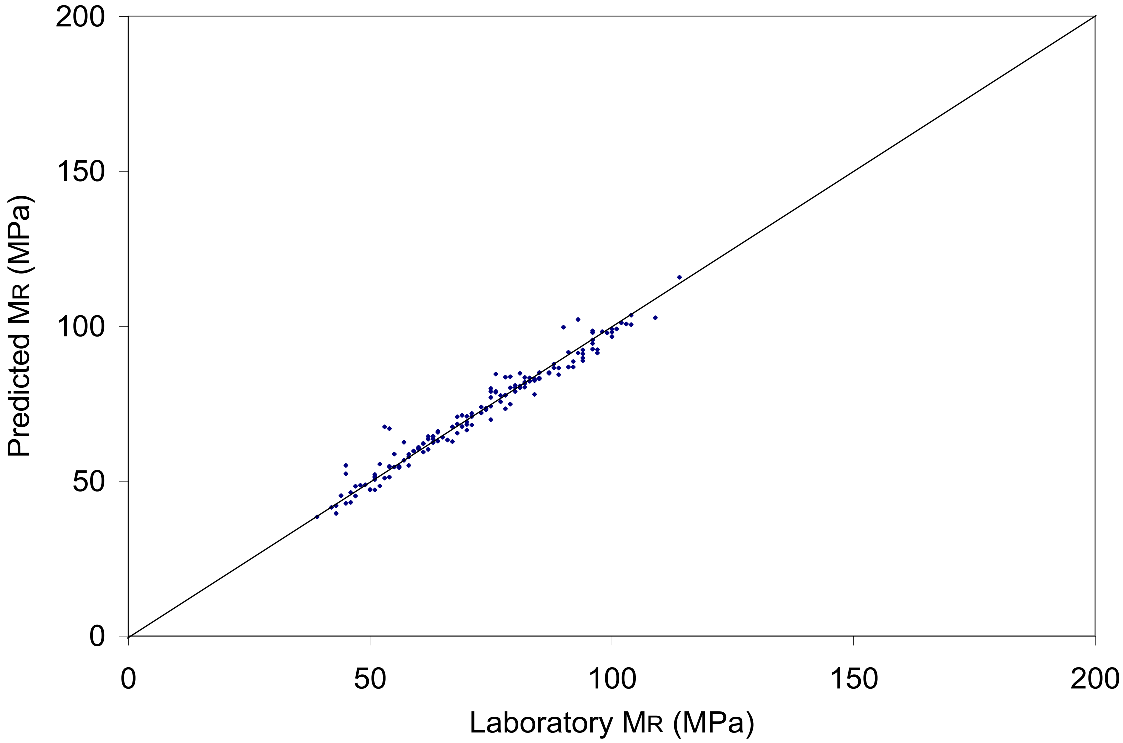


Figure 37. Predicted M_R vs. Laboratory M_R for samples compacted at optimum moisture content for A-1-b soils

- **Samples compacted at in-situ moisture content:**

Results of second step regression for the 19 A-1-b soil samples compacted at insitu moisture content have been presented in equations (14), (15), and (16) below.

$$\log k_1 = 1.78349 - 0.03097 \times MC + 0.00772 \times LL - 0.01837 \times S1\_HALF - 0.01154 \times SN200 \quad (R^2 = 0.71;\ Adj.\ R^2 = 0.63) \qquad (14)$$

$$k_2 = -3.99018 - 0.06842 \times MC + 0.49482 \times MCR - 0.00185 \times DD + 2.83862 \times DDR + 0.06019 \times S2 - 0.00774 \times SN10 + 0.02423 \times SILT \quad (R^2 = 0.80;\ Adj.\ R^2 = 0.67) \qquad (15)$$

$$k_3 = -1.17525 - 0.01956 \times MC - 0.00702 \times PL + 0.02351 \times S3 - 0.01190 \times S1\_HALF \quad (R^2 = 0.60;\ Adj.\ R^2 = 0.49) \qquad (16)$$

M_R values predicted by substituting the predicted values of k coefficients given by equations (14), (15), and (16) in Eq. (5) were plotted against the laboratory measured M_R values. The plot has been shown in Figure 38. Numerical values of the predicted k coefficients can be found in Table D.13, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.1, Appendix C. The analysis of laboratory and predicted M_R showed that 73.05 % of predicted M_R values were within ± 10% of the laboratory M_R values and 98.94 % of predicted M_R values were within ± 20% of the laboratory M_R values.

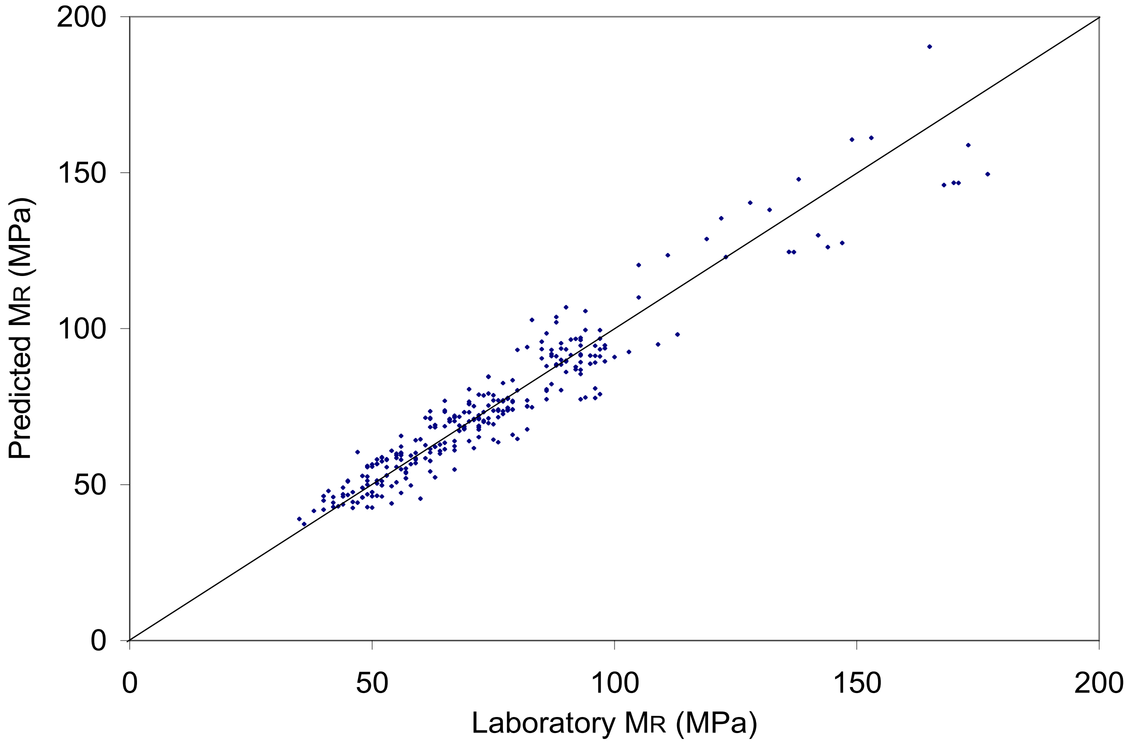


Figure 38. Predicted M_R vs. Laboratory M_R for samples compacted at insitu moisture content for A-1-b soils

4.3.3.2. Soil Type: A-3

In the first step regression analysis, 24 reconstituted samples from 11 states were analyzed for A-3 soils. Five samples resulted in R^2 less than 0.9 so only 19 samples were available for the second step regression. Among the 19 samples, 14 samples had been compacted at the optimum moisture content and 4 samples had been compacted at insitu moisture content. The results of second step regression for the 3 cases – All reconstituted samples, samples compacted at optimum moisture, and samples compacted at insitu moisture content have been presented below.

- **All reconstituted samples:**

The regression equations developed for the k coefficients for all reconstituted samples for A-3 soils are as given in Eq. (17), (18), and (19) below.

$$\log k_1 = -0.93681 - 0.01248 \times MC + 0.30352 \times MCR + 0.00020285 \times DD + 0.00194 \times FSAND \quad (R^2 = 0.47;\ Adj.\ R^2 = 0.32) \qquad (17)$$

$$k_2 = -0.13234 - 0.01724 \times MC + 0.02560 \times OMC + 0.00032543 \times DD + 0.00313 \times SN40 - 0.00291 \times SN80 - 0.01843 \times CLAY \quad (R^2 = 0.58;\ Adj.\ R^2 = 0.38) \qquad (18)$$

$$k_3 = -1.03002 + 0.09865 \times MCR + 0.00032615 \times DD + 0.00220 \times S1\_HALF + 0.00067403 \times SN40 \quad (R^2 = 0.76;\ Adj.\ R^2 = 0.69) \qquad (19)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (17), (18), and (19) along with 95% confidence interval lines has been presented in Figure 39, 40, and 41. Numerical values of the predicted k coefficients can be found in Table D.14, Appendix D.

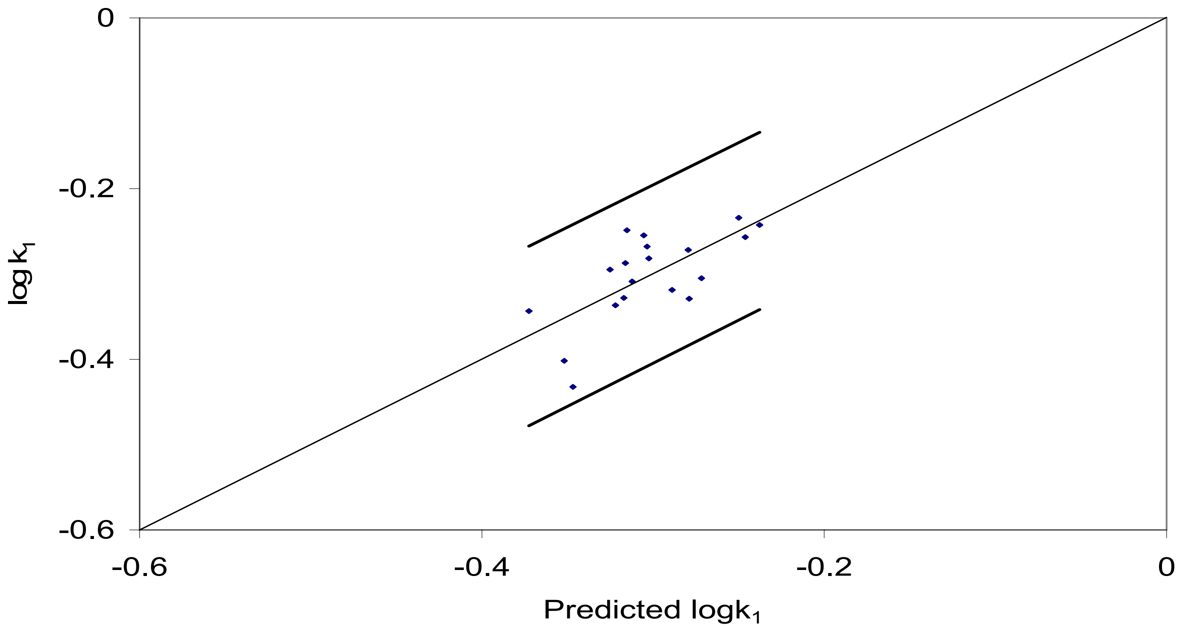


Figure 39. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-3 soils

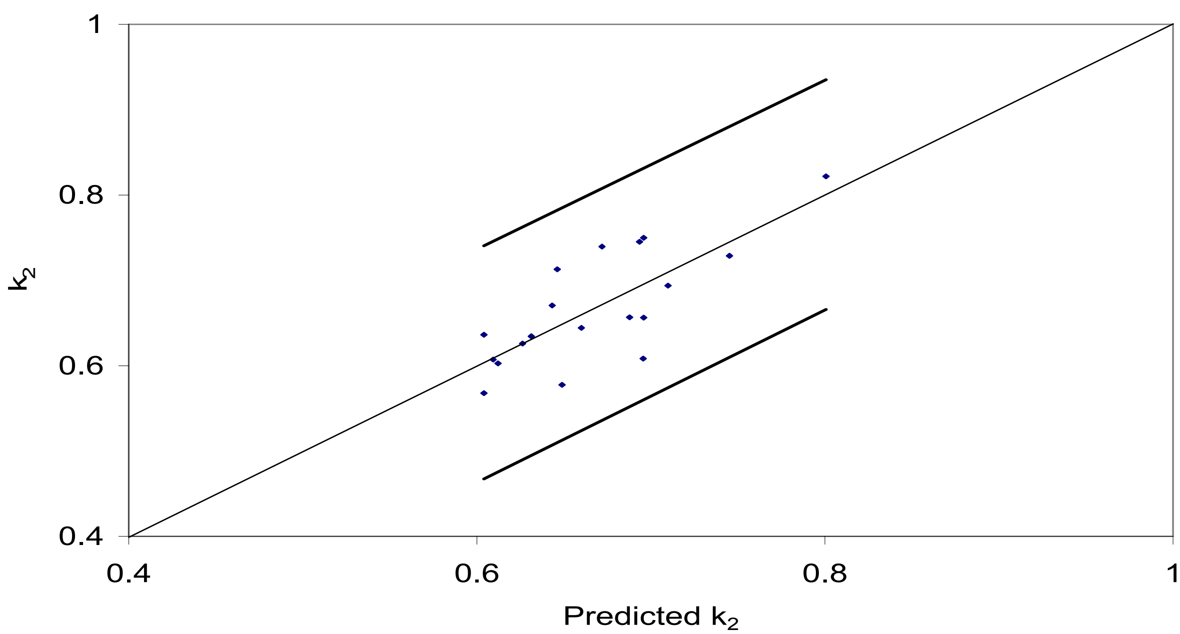


Figure 40. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-3 soils

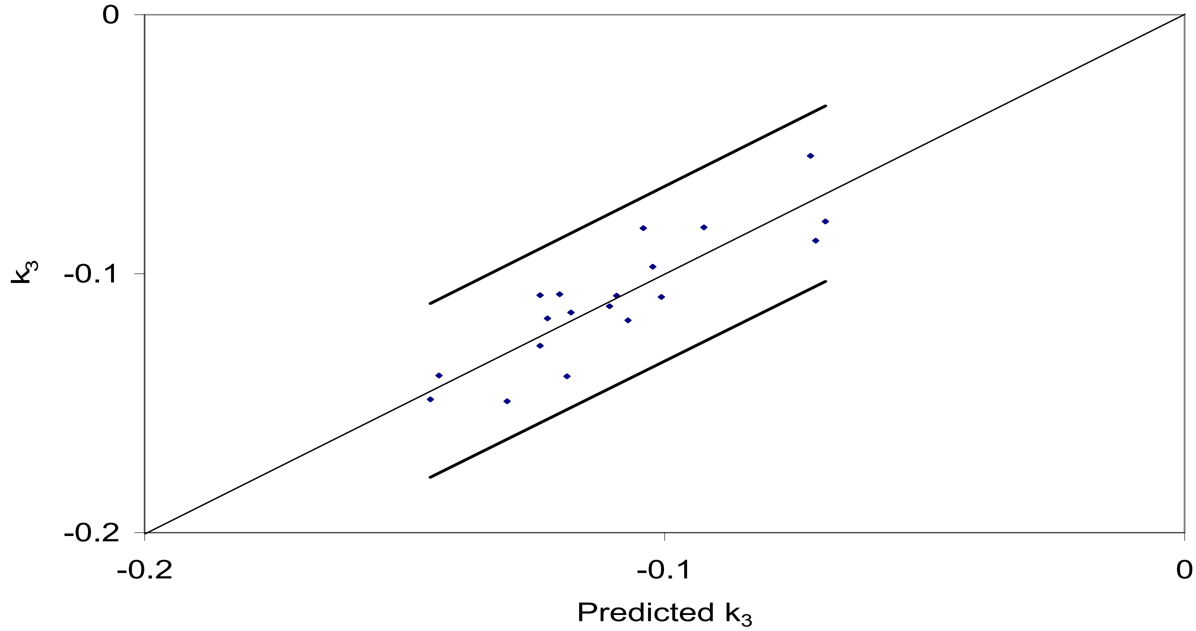


Figure 41. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-3 soils

Plot for M_R predicted by Eqs. (17), (18), and (19) and laboratory M_R has been show in Figure 42. Tabulated values of laboratory and predicted M_R values can be found in Table C.2, Appendix C. The analysis of laboratory and predicted M_R showed that 63.73 % of predicted M_R values were within ± 10% of the laboratory l M_R values and 94.72 % of predicted M_R values were within ± 20% of the laboratory M_R values.

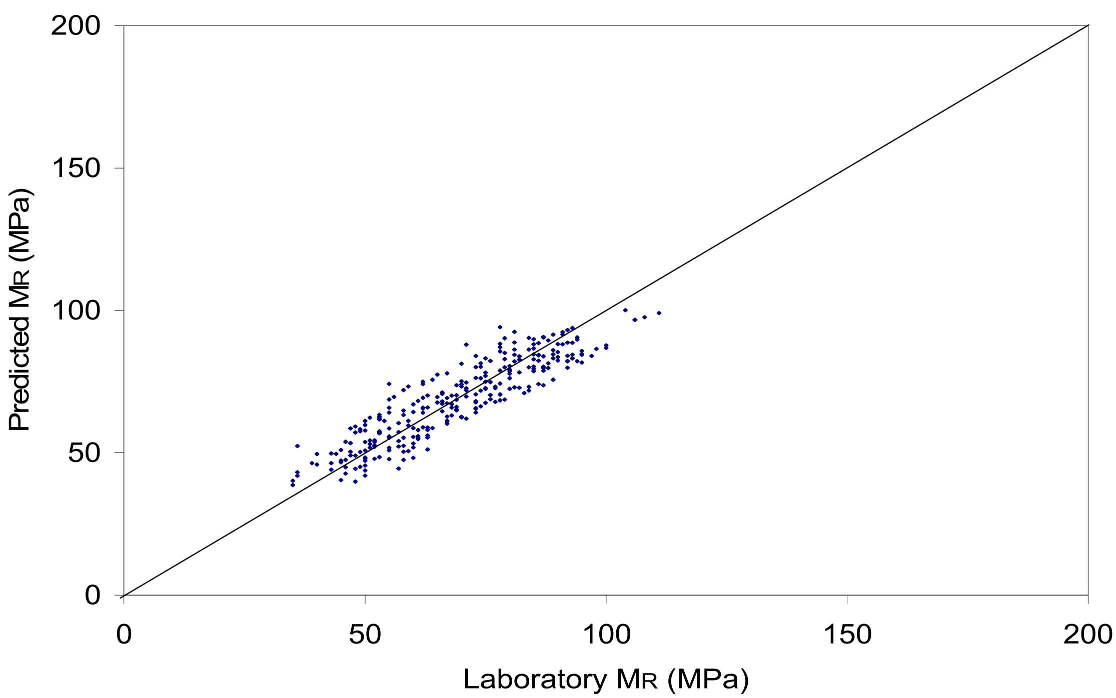


Figure 42. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-3 soils

- **Samples compacted at optimum moisture content:**

The results of second step regression to develop prediction models for the k coefficients for the 14 A-3 soil samples compacted at optimum moisture content have been presented in Eqs. (20), (21), and (22).

$$\log k_1 = -1.28763 - 0.01554 \times OMC - 1.59688 \times DDR + 0.04783 \times S1 - 0.02146 \times S3\_4 + 0.00124 \times SN80 \quad (R^2 = 0.72;\ Adj.\ R^2 = 0.55) \tag{20}$$

$$k_2 = -5.81794 + 0.00420 \times OMC + 0.42100 \times MCR - 2.53496 \times DDR + 0.06786 \times S1\_HALF + 0.01649 \times S3\_4 \quad (R^2 = 0.80;\ Adj.\ R^2 = 0.67) \tag{21}$$

$$k_3 = -0.78512 + 0.00270 \times OMC + 0.00032286 \times DD + 0.04002 \times S1\_HALF - 0.04000 \times S1 + 0.00119 \times SN40 - 0.00077438 \times SN80 + 0.00446 \times SILT \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.98) \tag{22}$$

Plot for the M_R predicted using predicted k coefficients from Eqs. (20), (21), and (22) and laboratory M_R values has been presented in Figure 43. Numerical values of the predicted k coefficients can be found in Table D.14, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.2, Appendix C. The analysis of laboratory and predicted M_R showed that 79.43 % of predicted M_R values were within ± 10% of the laboratory M_R values and 98.56 % of predicted M_R values were within ± 20% of the laboratory M_R values.

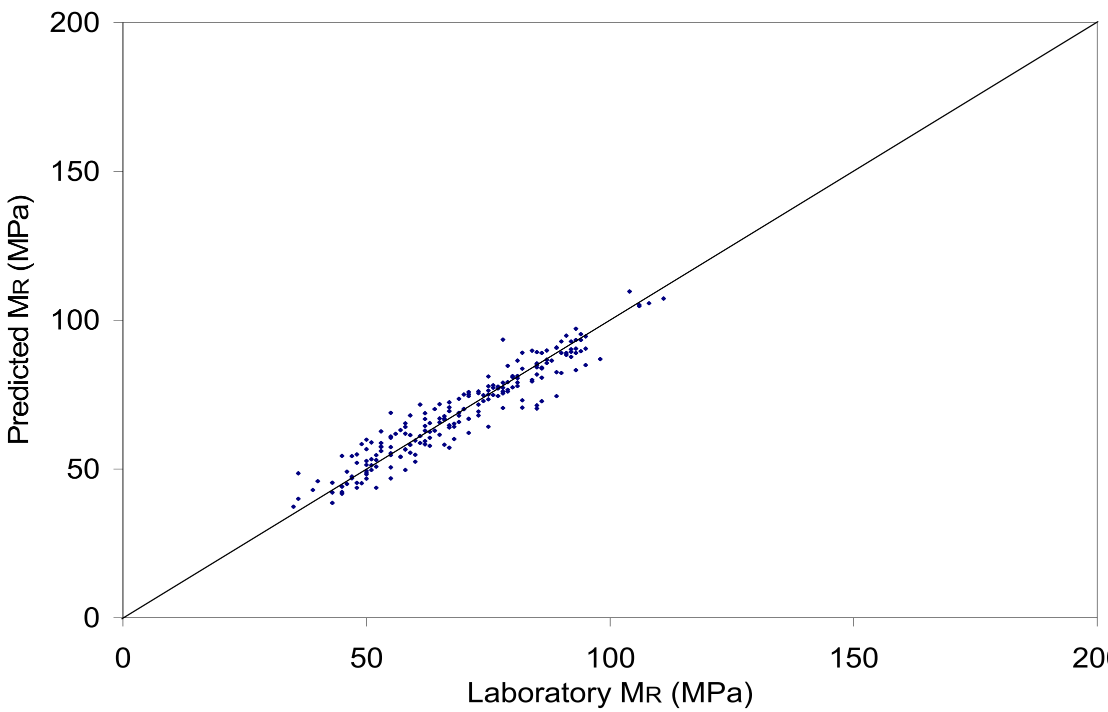


Figure 43. Predicted M_R vs. Laboratory M_R for samples compacted at optimum moisture content for A-3 soils

- **Samples compacted at insitu moisture content:**

There were only 4 samples compacted at insitu moisture content for A-3 soils. The data number here is too limited to carry out a statistically meaningful regression. However, regression equations have been developed from these 4 samples for completeness and have been presented in Eqs. (23), (24), and (25). These models should be used with caution.

$$\log k_1 = -1.80028 + 0.06083 \times MC + 0.09612 \times OMC \qquad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \qquad (23)$$

$$k_2 = 1.11468 - 0.03964 \times MC - 0.04803 \times CLAY \qquad (R^2 = 0.98;\ Adj.\ R^2 = 0.94) \qquad (24)$$

$$k_3 = 1.89076 - 0.08899 \times OMC - 0.00055406 \times MAXDD \qquad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \qquad (25)$$

Plot for M_R predicted from the predicted k values from Eqs. (23), (24), and (25) and the laboratory measured M_R values has been presented in Figure 44. Numerical values of the predicted k coefficients can be found in Table D.14, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.2, Appendix C. The analysis of laboratory and predicted M_R showed that 100% of predicted M_R values were within ± 10% of the laboratory M_R values and 100 % of predicted M_R values were within ± 20% of the laboratory M_R values.

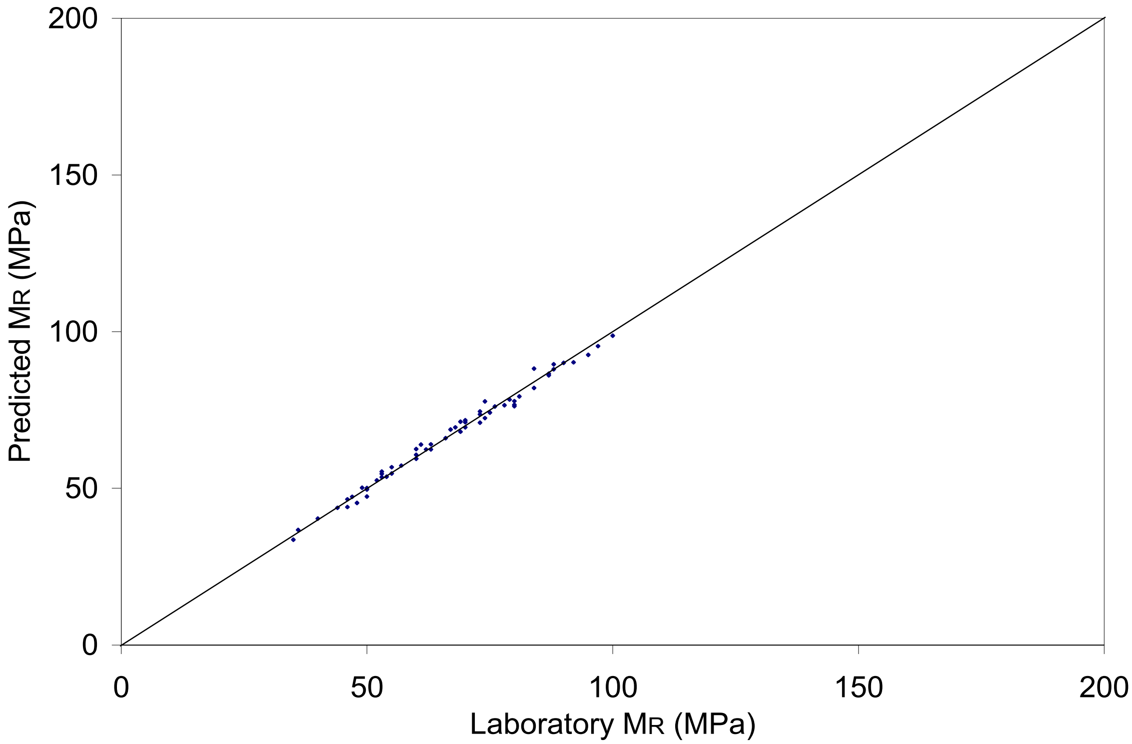


Figure 44. Predicted M_R vs. Laboratory M_R for samples compacted at insitu moisture content for A-3 soils

4.3.3.3. Soil Type: A-2-4

Fifty two test specimens from total of 13 states in the New England and nearby regions were initially analyzed to obtain the k coefficients for individual soil samples with the known laboratory M_R values using Eq. (5). Among these, 2 samples resulted in positive k_3, 5 samples resulted in R^2 less than 0.90, and 5 samples did not have PL and LL values reported in the LTPP database. These 12 samples were therefore not used for building the prediction models for k coefficients in the second step regression analysis that relates the k coefficients with the physical soil properties. The results of second step regression for A-2-4 soils have been presented below.

- **All reconstituted samples:**

The final regression equations obtained from the analysis to predict k_1, k_2, and k_3 for 40 reconstituted A-2-4 samples from 13 different states are as given below:

$$\log k_1 = 1.10795 - 0.02889 \times OMC - 0.23628 \times MCR - 0.67002 \times DDR - 0.01701 \times S2 + 0.01405 \times S3\_4$$
$$(R^2 = 0.37; \text{Adj. } R^2 = 0.28) \quad (26)$$

$$k_2 = -0.69772 + 0.02106 \times MC + 0.00054260 \times DD - 0.00657 \times LL + 0.00293 \times SN10 - 0.00460 \times SN200$$
$$(R^2 = 0.58; \text{Adj. } R^2 = 0.51) \quad (27)$$

$$k_3 = 0.50825 - 0.01956 \times OMC - 0.07234 \times MCR - 0.00492 \times LL - 0.00652 \times S2 + 0.00384 \times SN40 - 0.00153 \times SN80 + 0.00344 \times CLAY$$
$$(R^2 = 0.69; \text{Adj. } R^2 = 0.63) \quad (28)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (26), (27), and (28) along with 95% confidence interval lines have been presented in Figures 45, 46, and 47. Numerical values of predicted k-coefficients can be found in Table D.15, Appendix D.

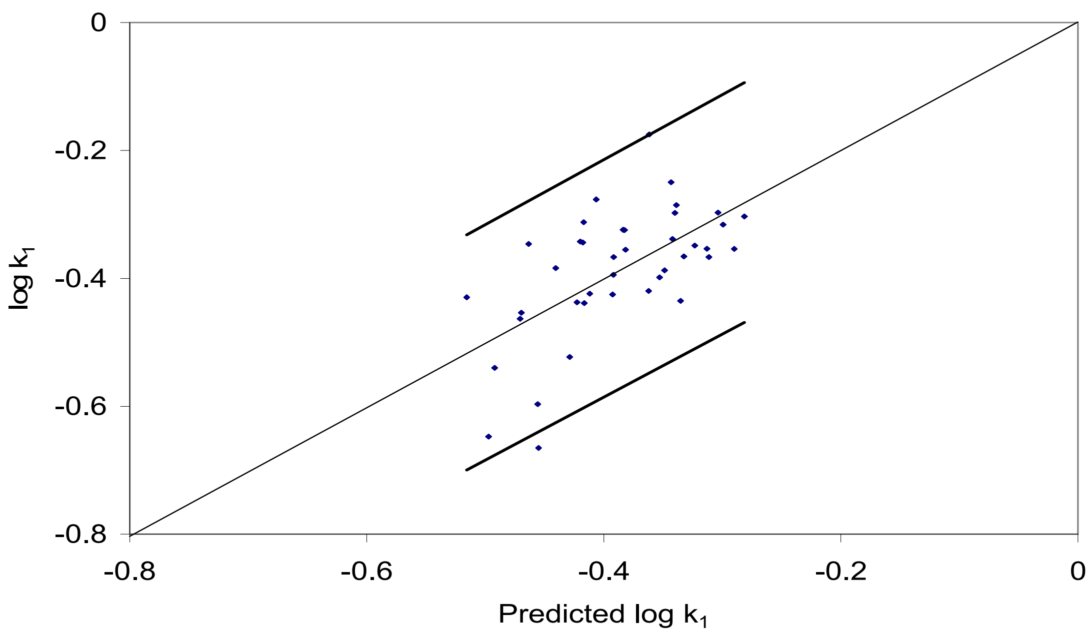


Figure 45. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-2-4 soils

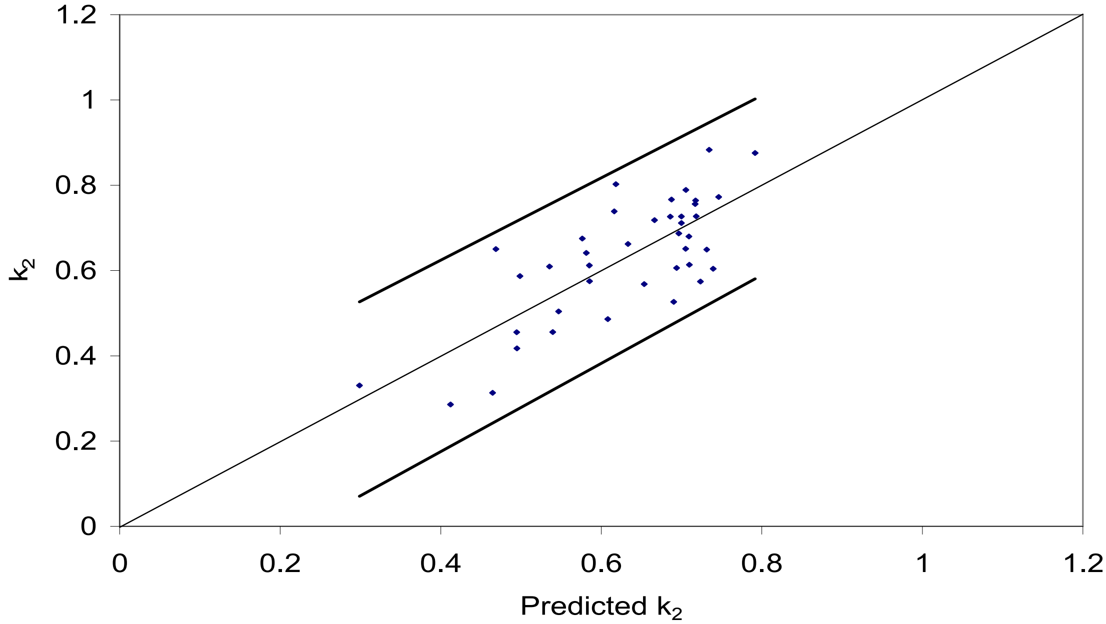


Figure 46. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-2-4 soils

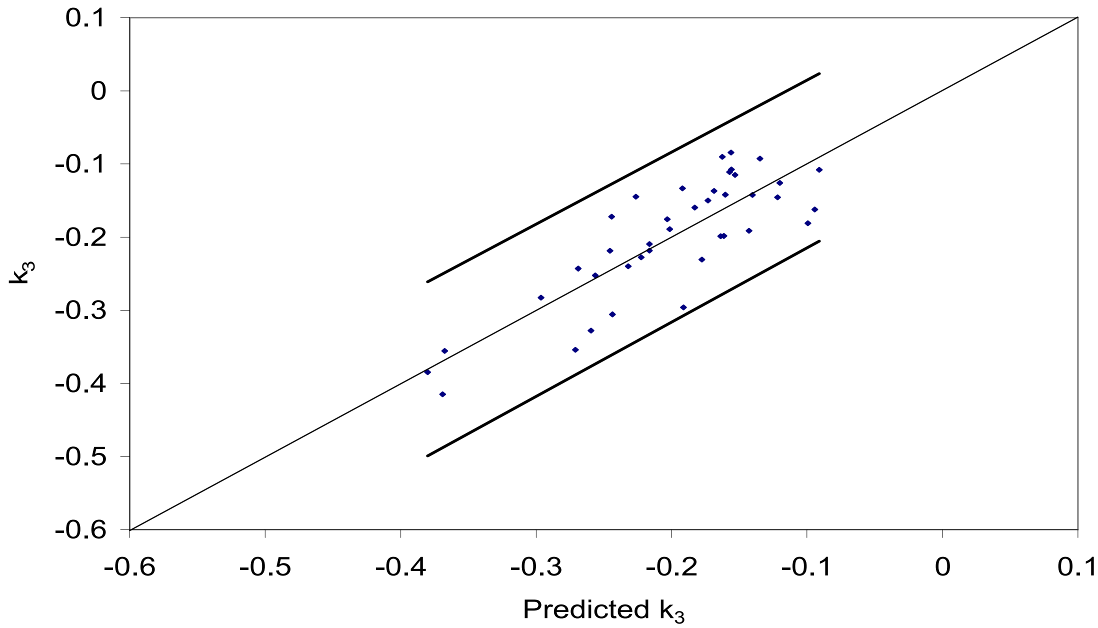


Figure 47. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-2-4 soils

The predicted values of M_R can now be obtained by substituting available soil physical properties values in the right hand side of Eqs. (26), (27), and (28) to determine k_1, k_2, and k_3 respectively, and then using these predicted values of k coefficients into Eq. (5). The plot for predicted M_R versus laboratory M_R has been shown in Figure 48. Detail numerical values of laboratory and predicted M_R values can be found in Table C.3, Appendix C. The analysis of laboratory and predicted M_R showed that 51.33 % of predicted M_R values were within ± 10% of the laboratory M_R values and 84.33 % of laboratory M_R values were within ± 20% of the actual M_R values

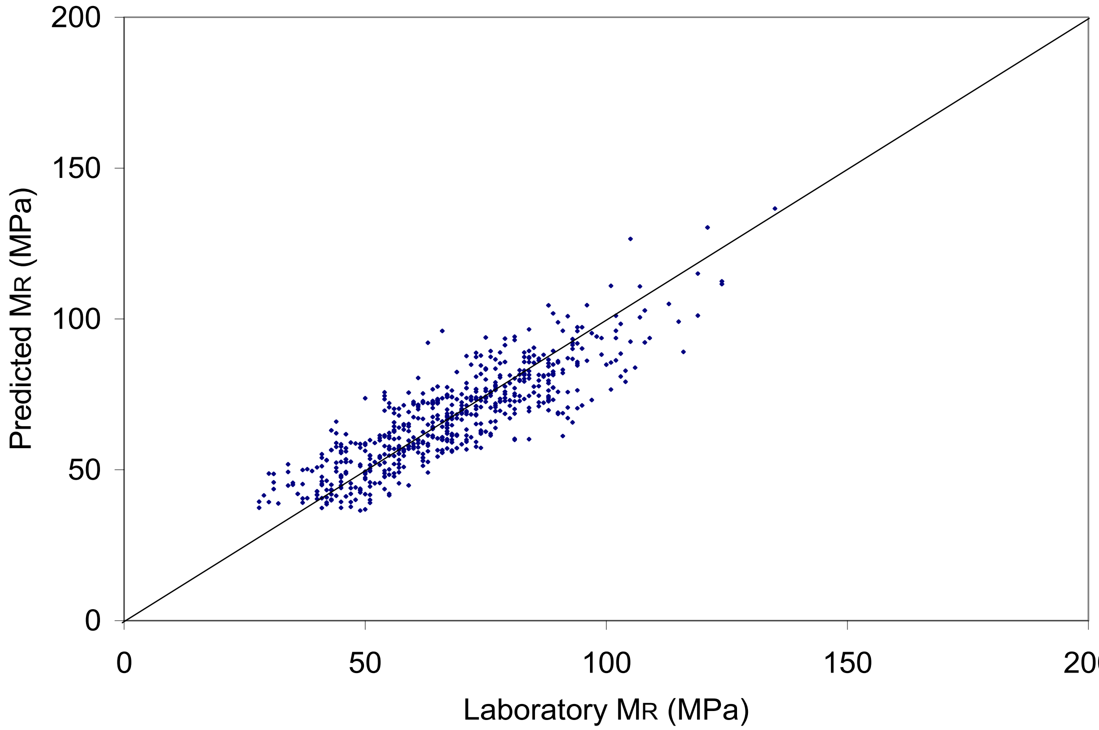


Figure 48. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-2-4 soils

- **Samples compacted at optimum moisture content:**

The results of second step regression to obtain the equations for k coefficients for the 28 A-2-4 soils from 12 different states that were compacted at optimum moisture content during resilient modulus testing have been presented below in Eqs. (29), (30), and (31).

$$\log k_1 = 2.01010 - 0.06696 \times OMC + 0.00057415 \times DD - 0.00095144 \times MAXDD - 0.04473 \times S2 + 0.03673 \times S1 - 0.00355 \times CSAND \quad (R^2 = 0.59;\ Adj.\ R^2 = 0.48) \quad (29)$$

$$k_2 = 2.05743 + 0.02542 \times OMC - 2.57064 \times DDR + 0.08047 \times S2 - 0.09125 \times S1 + 0.01852 \times S3\_8 - 0.00776 \times SN200 + 0.01014 \times CSAND \quad (R^2 = 0.78;\ Adj.\ R^2 = 0.70) \quad (30)$$

$$k_3 = 1.79954 - 0.05488 \times MC - 0.00061034 \times MAXDD - 0.00592 \times LL - 0.00917 \times S2 + 0.00751 \times S1\_2 - 0.00288 \times CSAND + 0.00440 \times CLAY \quad (R^2 = 0.86;\ Adj.\ R^2 = 0.81) \quad (31)$$

Plot for M_R predicted by substituting the value of k coefficients predicted by Eqs. (29), (30), and (31) into Eq. (5), and laboratory M_R has been shown in Figure 49. Numerical values of the predicted k coefficients can be found in Table D.15, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.3, Appendix C. The analysis of laboratory and predicted M_R showed that 64.37 % of predicted M_R values were within ± 10% of the laboratory M_R values and 89.31 % of predicted M_R values were within ± 20% of the laboratory M_R values.

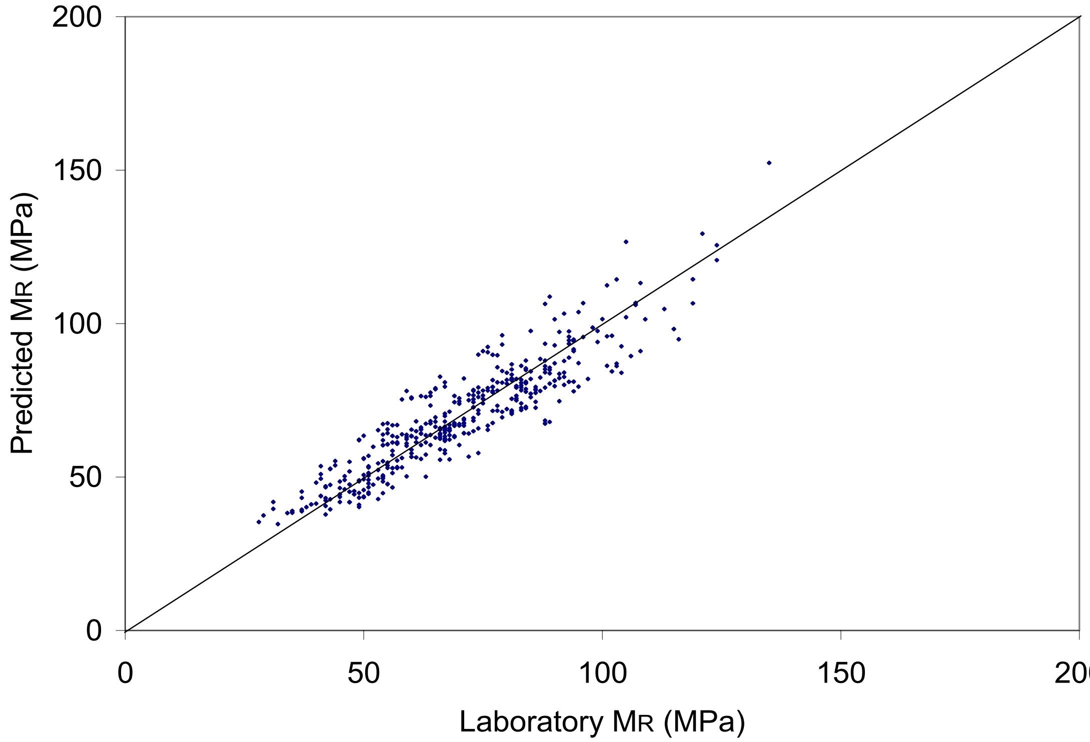


Figure 49. Predicted M_R vs. Laboratory M_R for samples compacted at optimum moisture content for A-2-4 soils

- **Samples compacted at insitu moisture content:**

Results of second step regression for the 12 A-2-4 soil samples compacted at insitu moisture content have been presented in Eqs. (32), (33), and (34) below.

log_k1 = 1.05873 - 0.13450 x MCR + 0.00045768 x MAXDD - 0.00905 x LL - 0.02172 x S3 + 0.00269 x SN80 - 0.00982 x SILT (R^2 = 0.99; Adj. R^2 = 0.98) (32)

k_2 = - 1.58669 + 0.01953 x OMC + 0.00036406 x DD + 0.01688 x S1_2 - 0.00949 x SN80 - 0.01289 x CSAND + 0.02220 x SILT (R^2 = 0.99; Adj. R^2 = 0.97) (33)

k_3 = - 1.26595 + 0.01043 x MC + 0.00070217 x DD - 0.01068 x SN200 - 0.00971 x CSAND (R^2 = 0.79; Adj. R^2 = 0.66) (34)

M_R values predicted by substituting the predicted values of k coefficients given by Eqs. ((32), (33), and (34) in Eq. (5) were plotted against the laboratory measured M_R values. The plot has been shown in Figure 50. Numerical values of the predicted k coefficients can be found in Table D.15, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.3, Appendix C. The analysis of laboratory and predicted M_R showed that 85.56 % of predicted M_R values were within ± 10% of the laboratory M_R values and 100 % of predicted M_R values were within ± 20% of the laboratory M_R values.

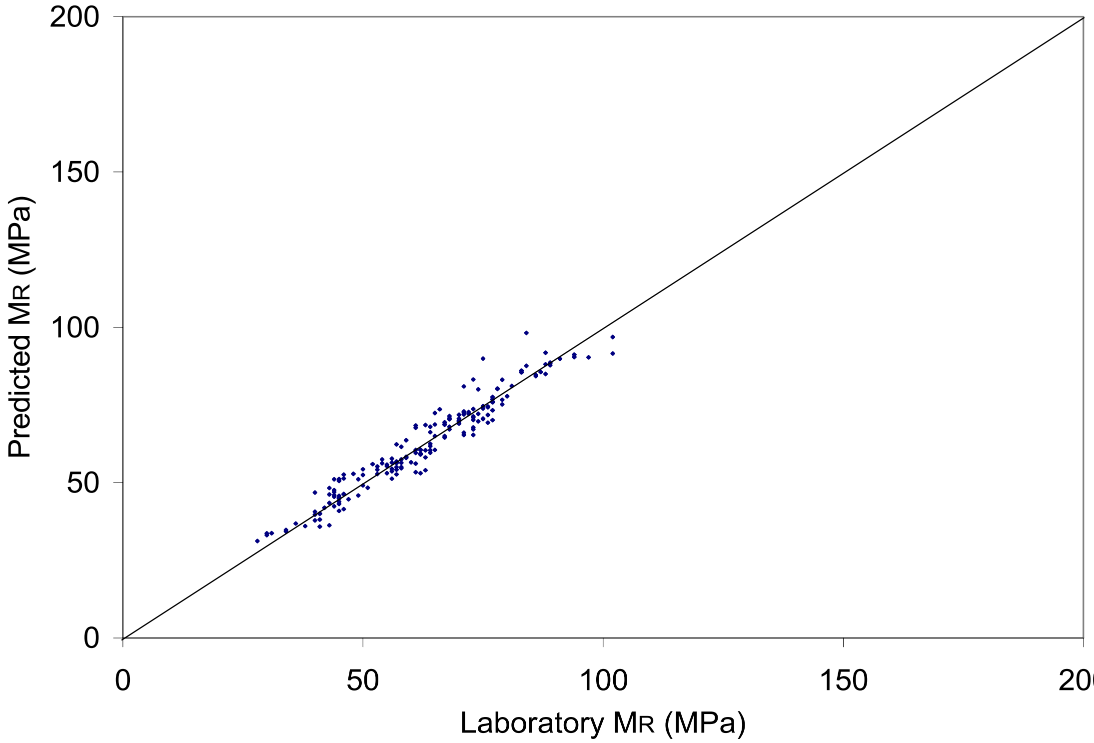


Figure 50. Predicted M_R vs. Laboratory M_R for samples compacted at insitu moisture content for A-2-4 soils

4.3.3.4. Soil Type: A-4

Eighty four test specimens from 16 states in New England and nearby regions were initially analyzed to obtain the value of k-coefficients (k_1, k_2, and k_3) for individual specimen with the known laboratory measured M_R values using Eq. (5). However, among these, 5 samples had positive k_3 and 13 samples had in R^2 less than 0.90. Therefore, the prediction models for k coefficients were developed on 66 samples only. Among the 66 samples, 41 samples had been compacted at optimum moisture content and 25 samples had been compacted at insitu moisture content.

- **All reconstituted samples:**

The regressions equations for k_1, k_2, and k_3 for the 66 reconstituted samples are found as given below (Eqs. (35), (36), and (37)).

$$\log k_1 = 5.74999 - 0.13693 \times OMC - 0.79256 \times MCR - 0.00161 \times MAXDD - 0.01092 \times S1 + 0.00591 \times SN200 + 0.00774 \times CLAY \quad (R^2 = 0.52;\ Adj.\ R^2 = 0.47) \quad (35)$$

$$k_2 = -0.74402 + 0.03585 \times MC + 0.0004803 \times DD + 0.00641 \times PL - 0.00839 \times LL + 0.00484 \times SN10 - 0.00477 \times SN80 - 0.00994 \times CLAY \quad (R^2 = 0.54;\ Adj.\ R^2 = 0.48) \quad (36)$$

$$k_3 = 1.30193 - 0.02367 \times MC - 0.02764 \times OMC - 0.0006325 \times MAXDD + 0.00156 \times SN10 + 0.00253 \times SILT \quad (R^2 = 0.30;\ Adj.\ R^2 = 0.24) \quad (37)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (35), (36), and (37) along with 95% confidence interval lines has been presented in Figures 51, 52, and 53. Numerical values of these predicted k coefficients can be found in Table D.16, Appendix D.

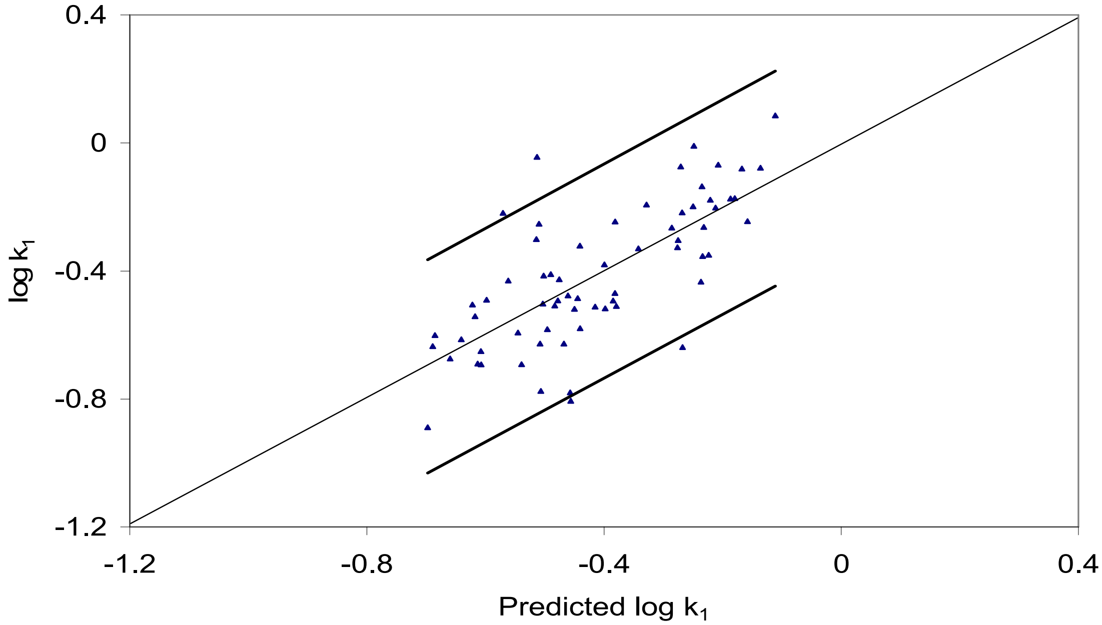


Figure 51. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-4 soils

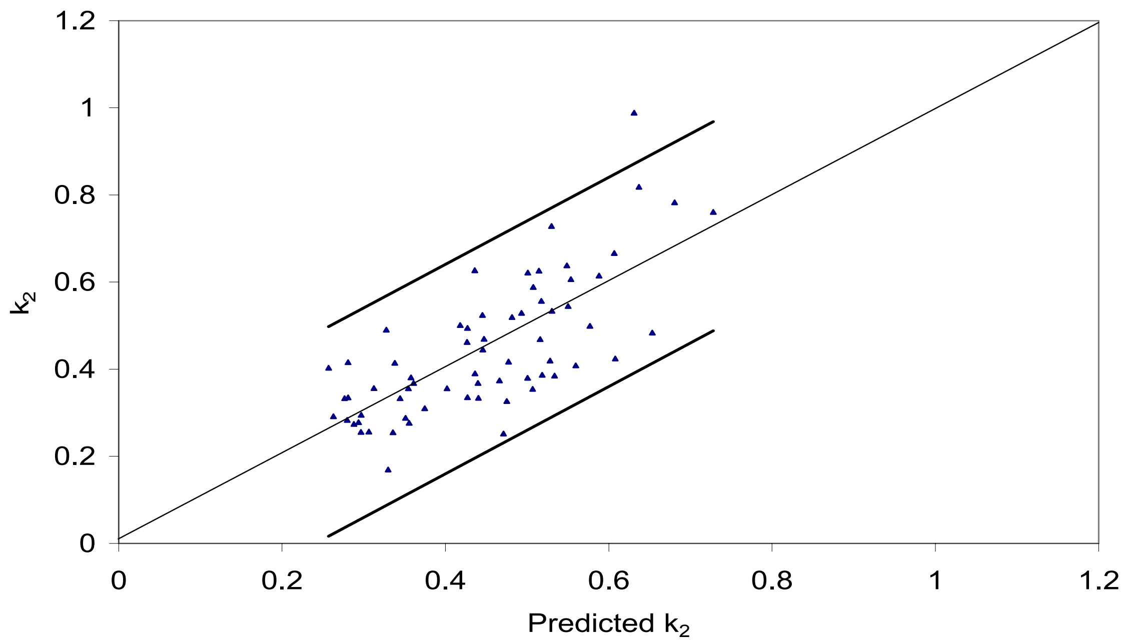


Figure 52. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-4 soils

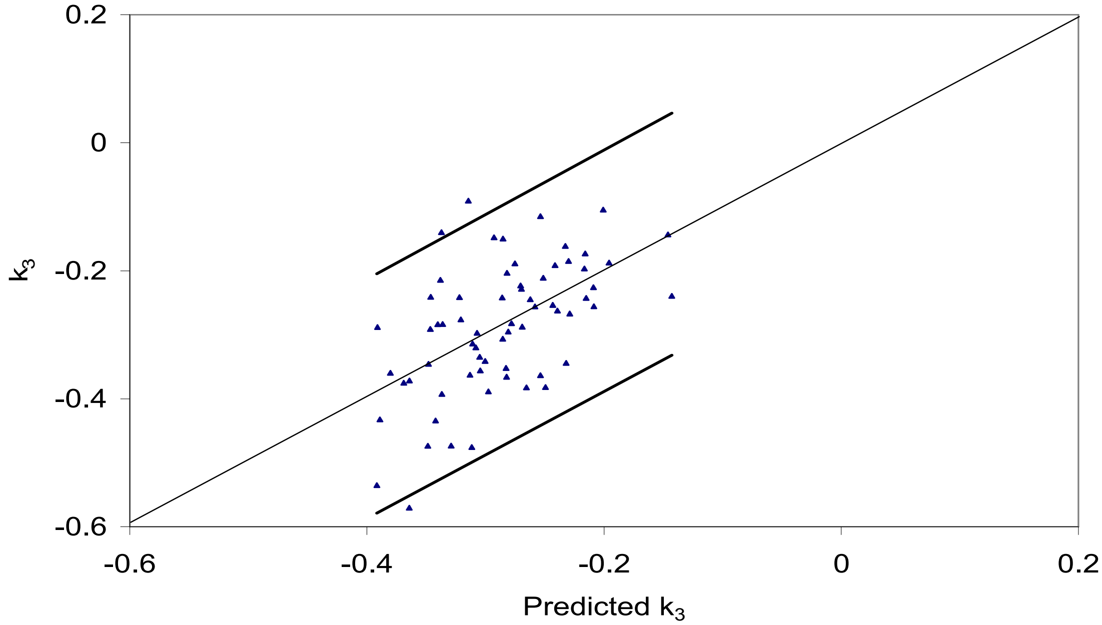


Figure 53. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-4 soils

The M_R values now can be predicted by substituting the corresponding values of physical properties of soils in the right side of Eqs. (35), (36), and (37) to determine k-values and then substituting these values of k coefficients into Eq. (5). The plot for predicted M_R versus laboratory M_R has been shown in Figure 54. Numerical values of laboratory and predicted M_R values can be found in Table C.4, Appendix C. The analysis of laboratory and predicted M_R showed that 35.53 % of predicted M_R values were within ± 10% of the laboratory M_R values and 62.15 % of predicted M_R values were within ± 20% of the laboratory M_R values.

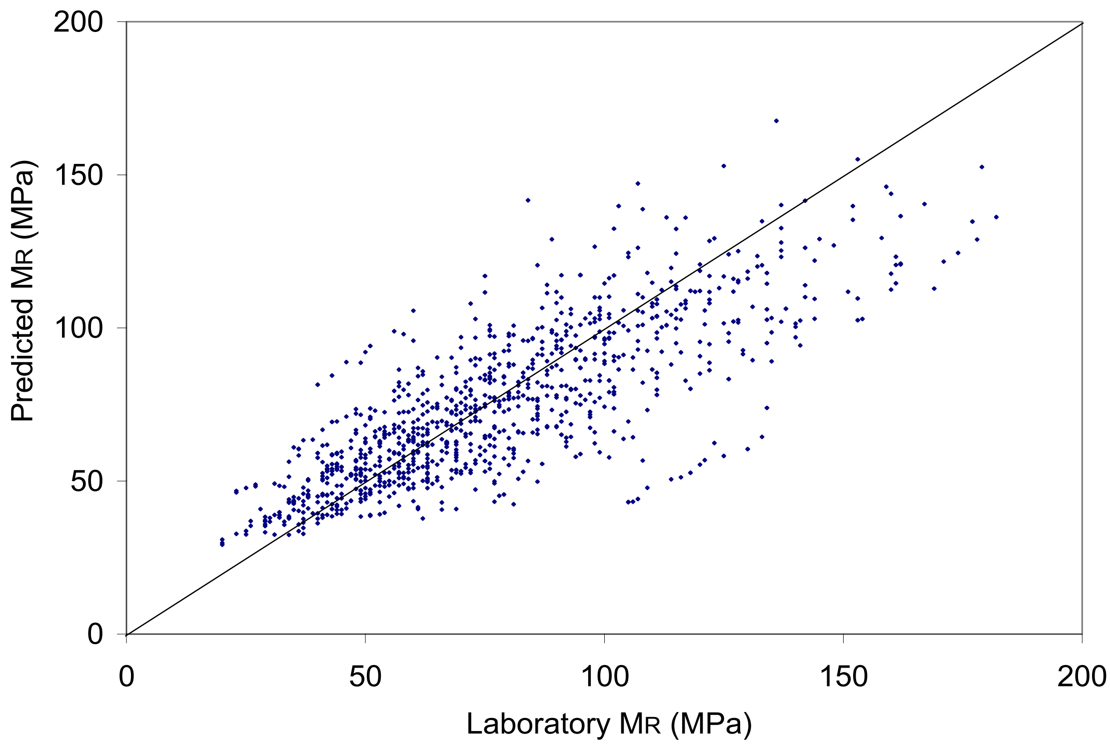


Figure 54. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-4 soils

- **Samples compacted at optimum moisture content:**

Regression equations developed for the k coefficients for the 41 samples from 13 different states compacted at optimum moisture content have been presented below (Eqs. (38), (39), and (40)).

$$\log k_1 = 3.60888 - 0.13212 \times MC - 0.00161 \times MAXDD + 0.02140 \times S1\_HALF - 0.01936 \times S3\_4 + 0.00790 \times SN200 \quad (R^2 = 0.52;\ Adj.\ R^2 = 0.45) \quad (38)$$

$$k_2 = -3.29043 + 0.05316 \times OMC + 0.00126 \times DD - 0.00468 \times PL + 0.01264 \times S1 - 0.00819 \times CSAND - 0.00295 \times SILT - 0.01365 \times CLAY \quad (R^2 = 0.68;\ Adj.\ R^2 = 0.62) \quad (39)$$

$$k_3 = 1.93886 - 0.05933 \times MC - 0.00074630 \times MAXDD - 0.00271 \times SN80 - 0.01004 \times CSAND + 0.00420 \times SILT \quad (R^2 = 0.50;\ Adj.\ R^2 = 0.43) \quad (40)$$

Plot for predicted M_R calculated by substituting the values of k coefficients obtained by putting the values of the soil physical properties in Eqs. (38), (39), and (40) into Eq. (5), and laboratory M_R has been presented in Figure 55. Numerical values of the predicted k coefficients can be found in Table D.16, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.4, Appendix C. The analysis of laboratory and predicted M_R showed that 35.83 % of predicted M_R values were within ± 10% of the laboratory M_R values and 66.29 % of predicted M_R values were within ± 20% of the laboratory M_R values.

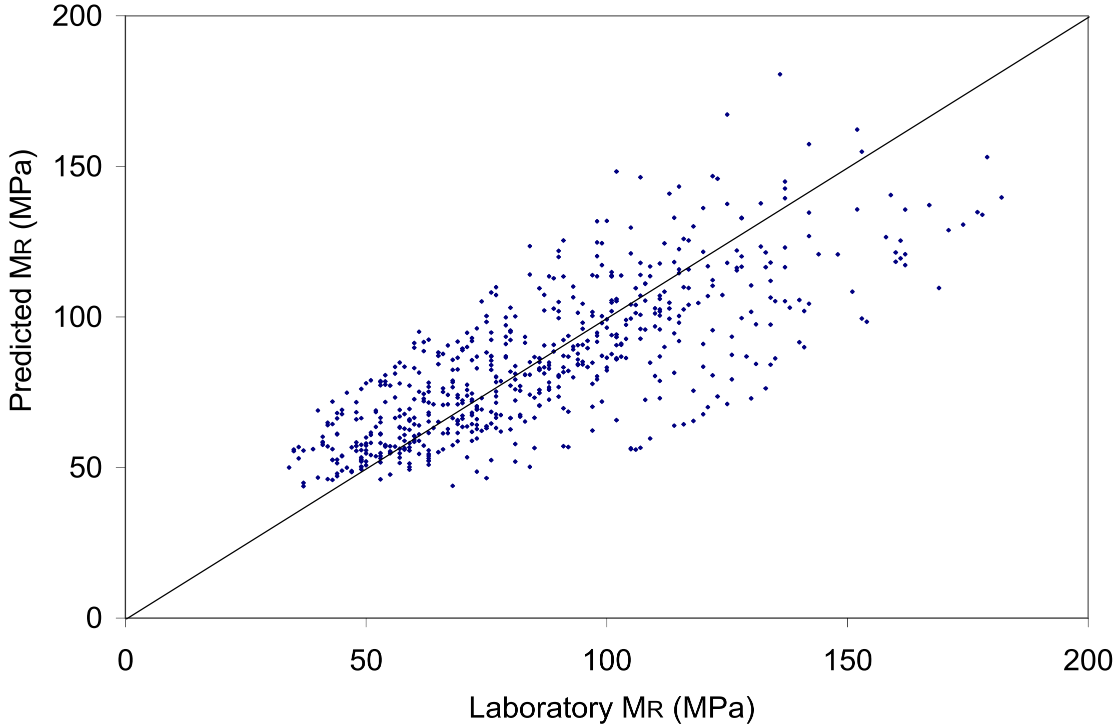


Figure 55. Predicted M_R vs. Laboratory M_R for samples compacted at optimum moisture content for A-4 soils

- **Samples compacted at insitu moisture content:**

Prediction models for the A-4 soil samples compacted at insitu moisture content obtained after second step regression has been given below (Eqs. (41), (42), and (43)).

$$\log k_1 = 12.04783 - 0.06409 \times MC - 0.06928 \times OMC - 0.00152 \times MAXDD - 0.12972 \times S1 + 0.04723 \times S3\_8 + 0.02535 \times CLAY \quad (R^2 = 0.70;\ Adj.\ R^2 = 0.60) \qquad (41)$$

$$k_2 = 1.55793 - 0.00018031 \times DD + 0.01067 \times PL - 0.03284 \times S3\_8 + 0.04736 \times SN10 - 0.02589 \times SN80 - 0.02342 \times CSAND \quad (R^2 = 0.77;\ Adj.\ R^2 = 0.69) \qquad (42)$$

$$k_3 = 3.18908 - 0.02399 \times MC - 0.05290 \times S1 + 0.02136 \times SN4 + 0.00317 \times CLAY \quad (R^2 = 0.42;\ Adj.\ R^2 = 0.30) \qquad (43)$$

The plot for predicted M_R values, obtained by substituting k coefficients from Eqs. (41), (42), and (43) into Eq. (5), against laboratory determined M_R values has been shown in Figure 56. Numerical values of the predicted k coefficients can be found in Table D.16, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.4, Appendix C. The analysis of laboratory and predicted M_R showed that 39.04 % of predicted M_R values were within ± 10% of the laboratory M_R values and 73.79 % of predicted M_R values were within ± 20% of the laboratory M_R values.

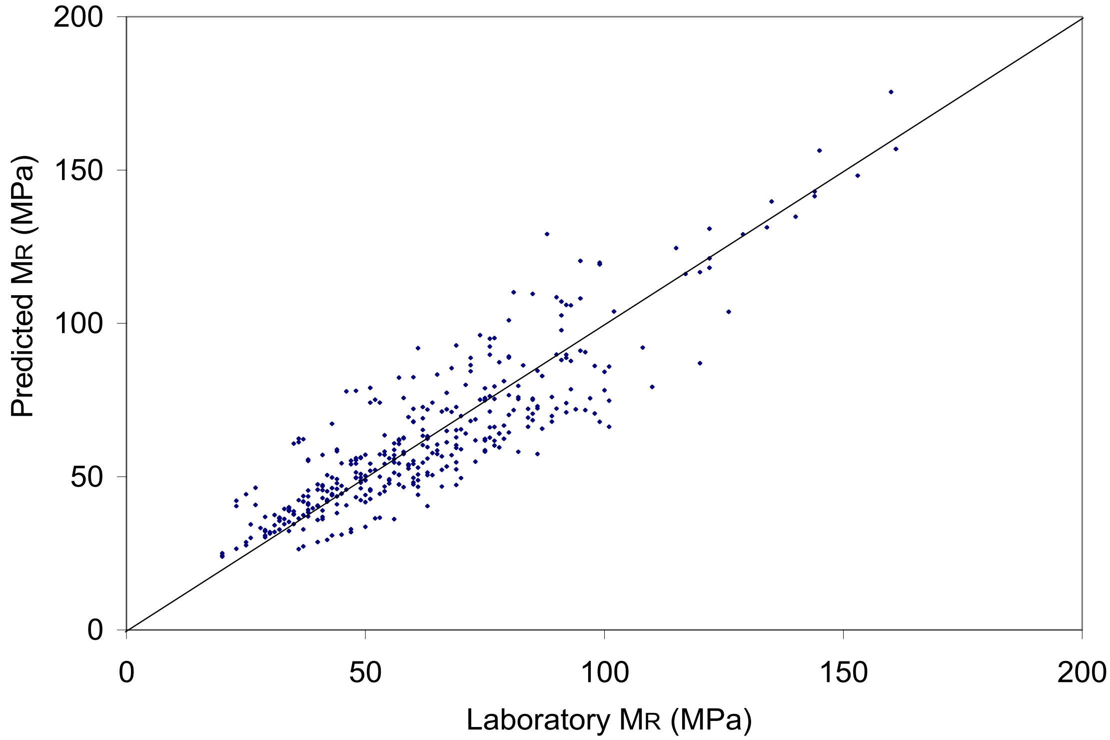


Figure 56. Predicted M_R vs. Laboratory M_R for samples compacted at insitu moisture content for A-4 soils

4.3.3.5. Soil Type: A-6

For regression to determine k coefficients of individual samples from known M_R and stress values using Eq. (5), 40 soil specimens from 13 states in regions nearby the New England region were analyzed. Data for A-6 soil samples were not available in the LTPP database for the New England region. Since 1 sample resulted in positive k_3 and 3 samples resulted in R^2 less than 0.90 during this regression, these 4 samples were not used in the subsequent analysis to develop regression equations for predicting k coefficients in terms of physical soil properties for this soil type. Out of 36 specimens taken for second step regression, 23 samples had been compacted at optimum moisture content and 13 had been compacted at insitu moisture content. The regression equations for k_1, k_2, and k_3 are given below:

- **All reconstituted samples:**

The final regression equations for k_1, k_2, and k_3 obtained from the second step regression analysis for 36 reconstituted samples are as given below:

$$\log k_1 = 4.59815 - 0.12918 \times MC - 0.00211 \times MAXDD + 0.04246 \times LL - 0.0150 \times CSAND - 0.01746 \times CLAY \quad (R^2 = 0.52;\ Adj.\ R^2 = 0.44) \quad (44)$$

$$k_2 = -2.54229 + 0.00971 \times MC + 0.00122 \times MAXDD + 0.02703 \times SN40 - 0.02122 \times SN200 - 0.02393 \times FSAND \quad (R^2 = 0.47;\ Adj.\ R^2 = 0.38) \quad (45)$$

$$k_3 = 2.08649 - 0.05214 \times MC - 0.0007171 \times MAXDD + 0.02450 \times LL - 0.01231 \times S1 + 0.00493 \times SN80 - 0.00922 \times CLAY \quad (R^2 = 0.49;\ Adj.\ R^2 = 0.38) \quad (46)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (44), (45), and (46) along with 95% confidence interval lines has been presented in Figures 57, 58, and 59. Numerical values of predicted k coefficients can be found in Table D.17, Appendix D.

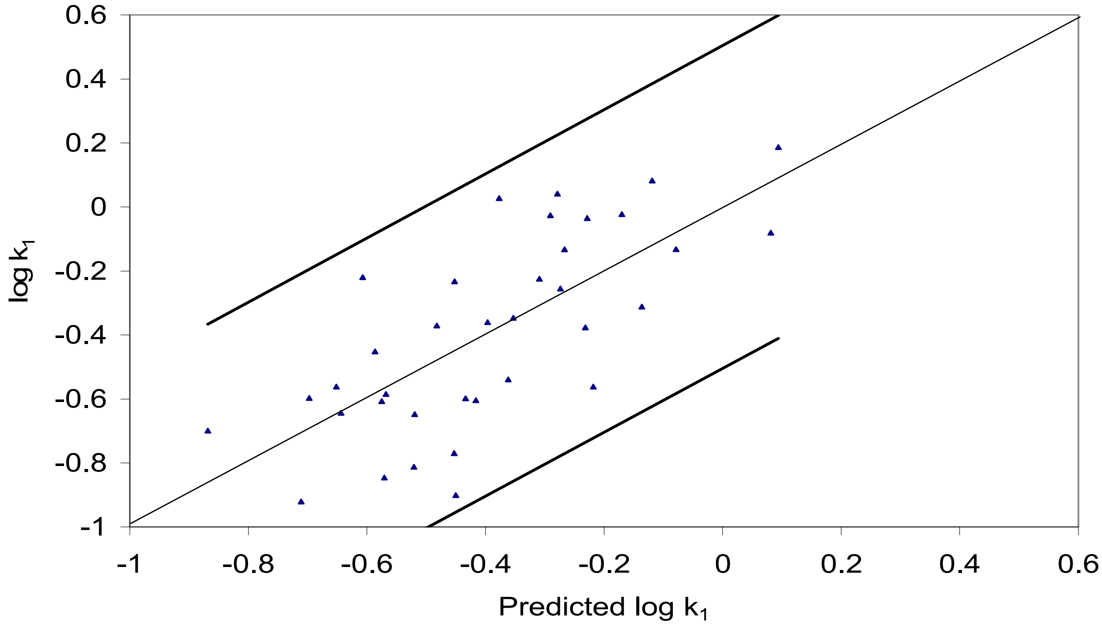


Figure 57. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-6 soils

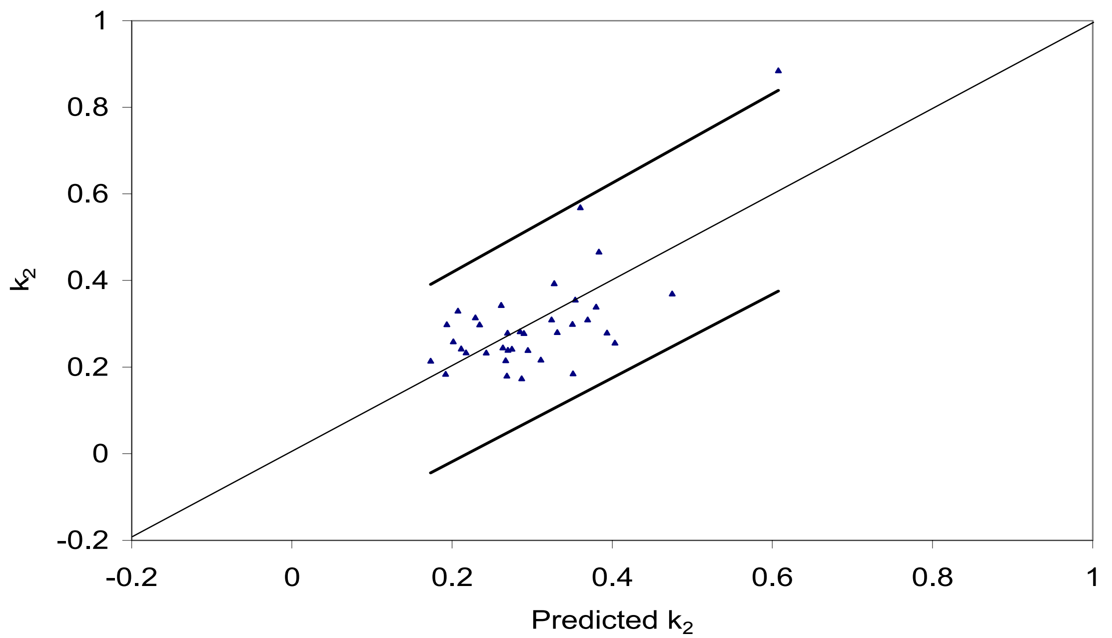


Figure 58. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-6 soils

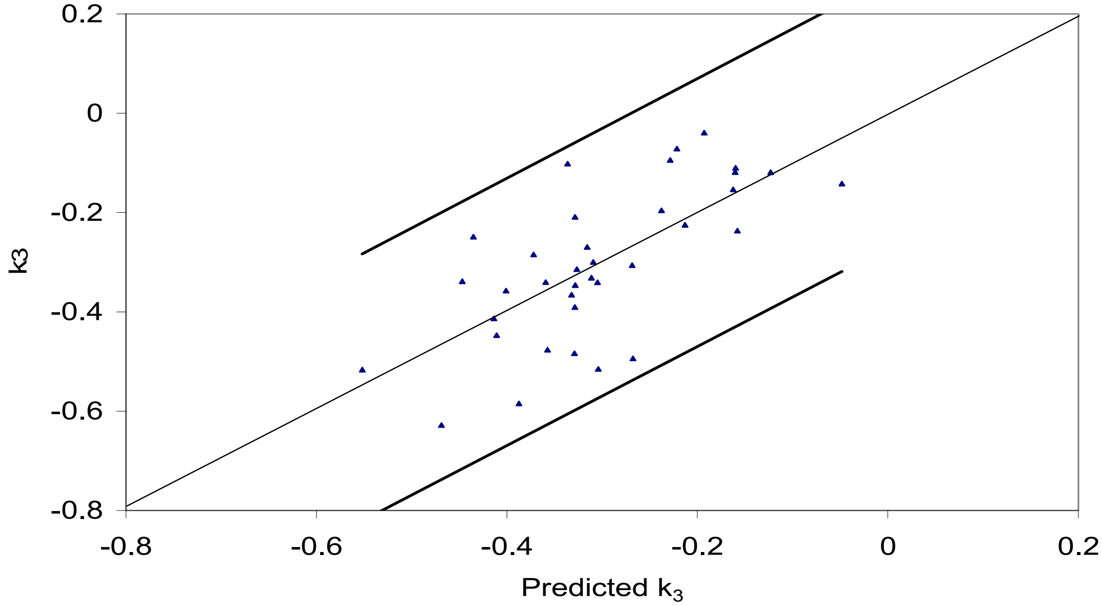


Figure 59. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-6 soils

The plot for predicted M_R values, obtained by substituting k coefficients from Eqs. (44), (45), and (46) into Eq. (5), against laboratory determined M_R values has been shown in Figure 60. Numerical values of laboratory and predicted M_R values can be found in Table C.5, Appendix C. The analysis of laboratory and predicted M_R showed that 22.59 % of predicted M_R values were within ± 10% of the laboratory M_R values and 42.96 % of predicted M_R values were within ± 20% of the laboratory M_R values.

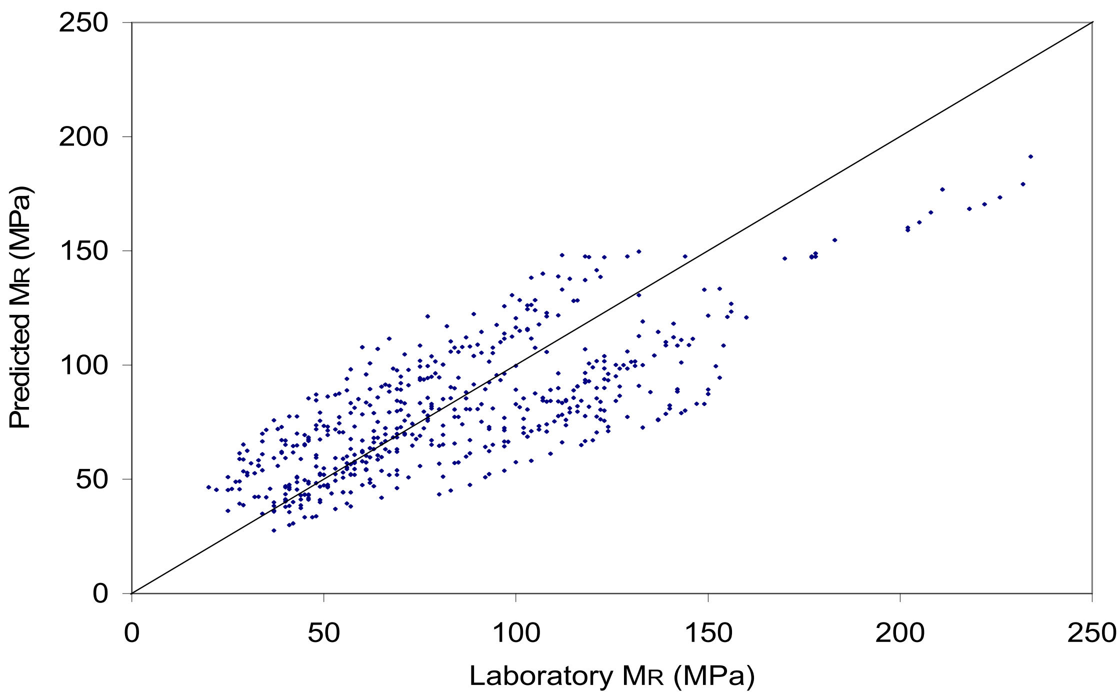


Figure 60. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-6 soils

- **Samples compacted at optimum moisture content:**

The regression equations for the k coefficients for 23 A-6 samples compacted at optimum moisture content are as given in Eqs. (47), (48), and (49).

$$\log k_1 = 11.43172 - 0.11840 \times MC + 0.07733 \times PL + 0.03185 \times LL - 0.16290 \times S2 + 0.04052 \times SN4 \quad (R^2 = 0.58; \text{Adj. } R^2 = 0.45) \quad (47)$$

$$k_2 = -3.39047 - 0.00037458 \times MAXDD - 0.01423 \times LL + 0.06384 \times S2 - 0.01620 \times SN4 \quad (R^2 = 0.45; \text{Adj. } R^2 = 0.32) \quad (48)$$

$$k_3 = 5.70946 - 0.05880 \times MC + 0.04341 \times PL + 0.01976 \times LL - 0.08633 \times S2 + 0.02200 \times SN4 \quad (R^2 = 0.55; \text{Adj. } R^2 = 0.42) \quad (49)$$

Figure 61 shows the plot of predicted M_R obtained from the predicted k coefficients using Eqs. (47), (48), and (49) and laboratory measured M_R values for the A-6 soil samples compacted at optimum moisture content. Numerical values of the predicted k coefficients can be found in Table D.17, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.5, Appendix C. The analysis of laboratory and predicted M_R showed that 33.62 % of predicted M_R values were within ± 10% of the laboratory M_R values and 57.10 % of predicted M_R values were within ± 20% of the laboratory M_R values.

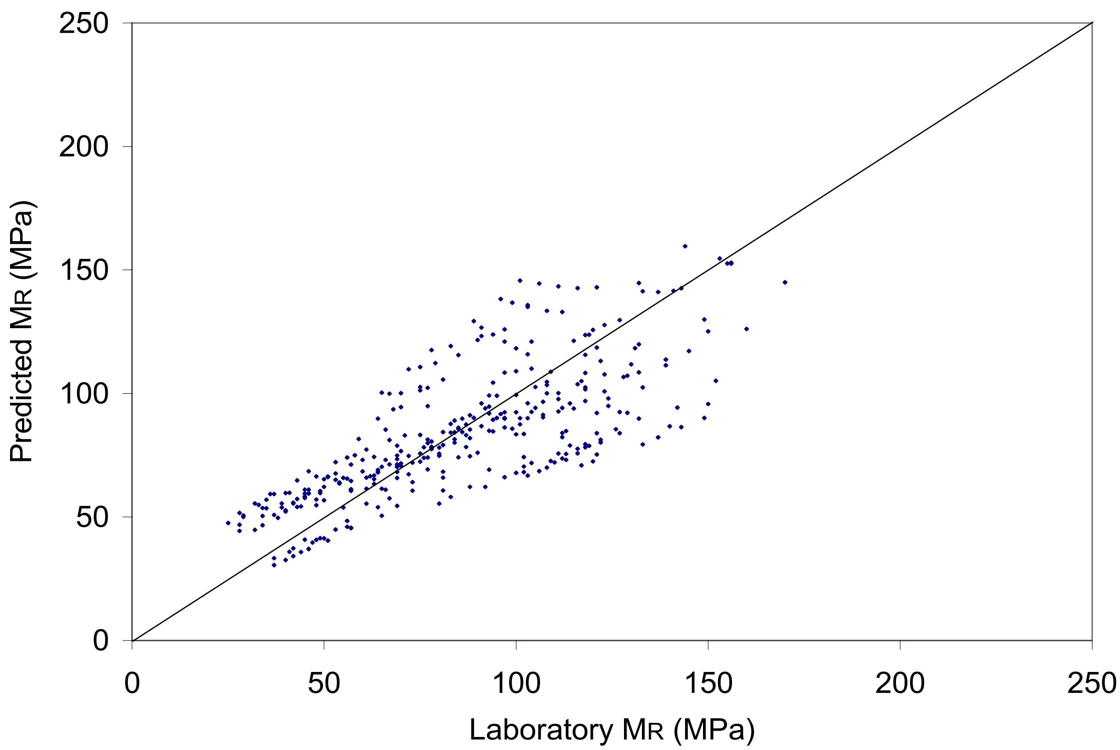


Figure 61. Predicted M_R vs. Laboratory M_R for soil samples compacted at optimum moisture content for A-6 soils

- **Samples compacted at insitu moisture content:**

Prediction models for the A-6 soil samples compacted at insitu moisture content obtained after second step regression has been given below (Eqs. (50), (51), and (52)).

$$log\_k1 = 17.64679 - 0.00330 \times MAXDD - 0.17669 \times PL - 0.10358 \times S1\_2 + 0.04379 \times CLAY$$
$$(R^2 = 0.78; Adj.\ R^2 = 0.66) \quad (50)$$

$$k2 = 0.35299 - 0.03880 \times OMC + 0.08025 \times PL - 0.04909 \times LL + 0.00939 \times SN80$$
$$(R^2 = 0.80; Adj.\ R^2 = 0.71) \quad (51)$$

$$k3 = 8.60279 - 0.00107 \times DD - 0.06858 \times PL - 0.06568 \times S3\_4 + 0.01672 \times SN80 - 0.01271 \times SILT$$
$$(R^2 = 0.68; Adj.\ R^2 = 0.46) \quad (52)$$

Figure 62 shows the plot of predicted M_R obtained from the predicted k coefficients using Eqs. (50), (51), and (52) and laboratory measured M_R values for the A-6 soil samples compacted at insitu moisture content. Numerical values of the predicted k coefficients can be found in Table D.17, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.5, Appendix C. The analysis of laboratory and predicted M_R showed that 41.03 % of predicted M_R values were within ± 10% of the laboratory M_R values and 70.26 % of predicted M_R values were within ± 20% of the laboratory M_R values.

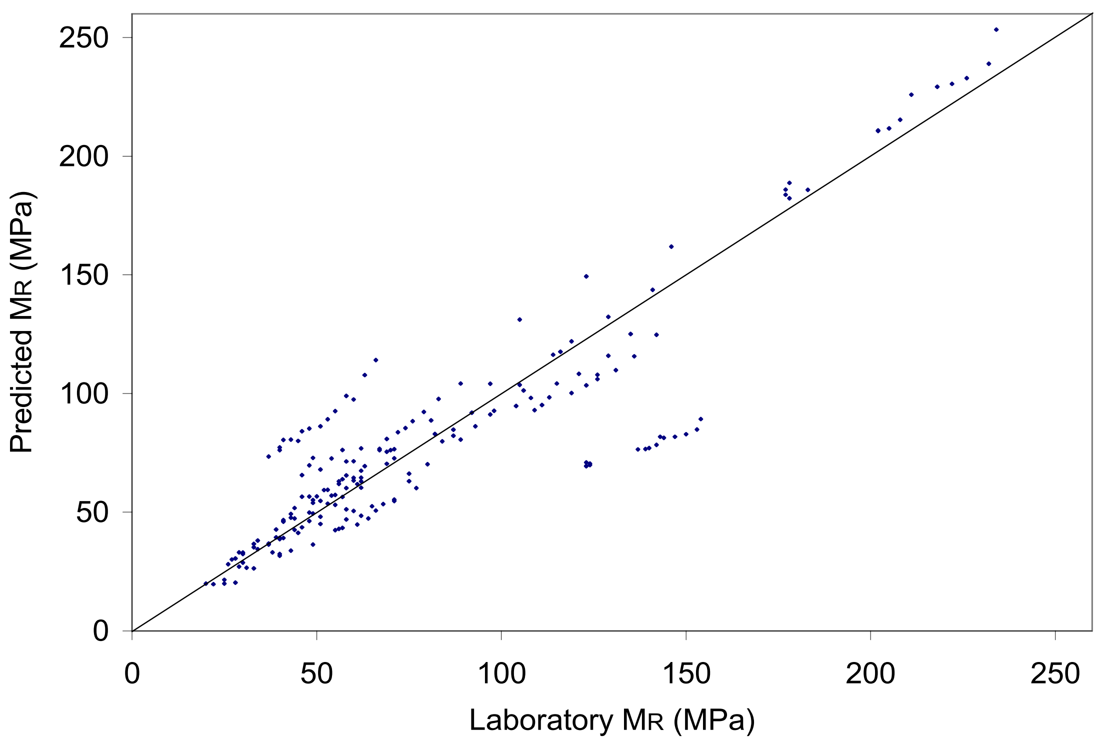


Figure 62. Predicted M_R vs. Laboratory M_R for soil samples compacted at insitu moisture content for A-6 soils

4.3.3.6. Soil Type: A-7-6

Twenty five test specimens from 9 states in New England and nearby regions were initially analyzed to obtain the value of k-coefficients (k_1, k_2, and k_3) for individual specimen with the known laboratory measured M_R values using Eq. (5). However, among these, 1 sample had Record Status "D" and 4 samples had R^2 less than 0.90. Therefore, the prediction models for k coefficients were developed on 20 samples only. Among the 20 samples, 13 samples had been compacted at optimum moisture content and 7 samples had been compacted at insitu moisture content. The results of second step regression to develop prediction models for k_1, k_2, and k_3 have been presented below.

- **All reconstituted samples:**

The regressions equations for k_1, k_2, and k_3 for the 20 reconstituted samples are found as given below (Eqs. (53), (54), and (55)).

$$\log k_1 = 6.54551 - 0.08119 \times MC - 0.00202 \times MAXDD - 0.00719 \times PL - 0.01842 \times SN200 - 0.06529 \times CSAND \quad (R^2 = 0.79; \text{Adj. } R^2 = 0.72) \quad (53)$$

$$k_2 = 9.78523 + 0.00743 \times MC - 0.00018782 \times DD - 0.01787 \times LL - 0.08598 \times S1\_HALF \quad (R^2 = 0.45; \text{Adj. } R^2 = 0.30) \quad (54)$$

$$k_3 = 3.38876 - 0.03515 \times MC - 0.00121 \times MAXDD - 0.01073 \times PL - 0.00711 \times SN200 - 0.02667 \times CSAND \quad (R^2 = 0.70; \text{Adj. } R^2 = 0.60) \quad (55)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (53), (54), and (55) along with 95% confidence interval lines has been presented in Figures 63, 64, and 65. Numerical values of predicted k coefficients can be found in Table D.18, Appendix D.

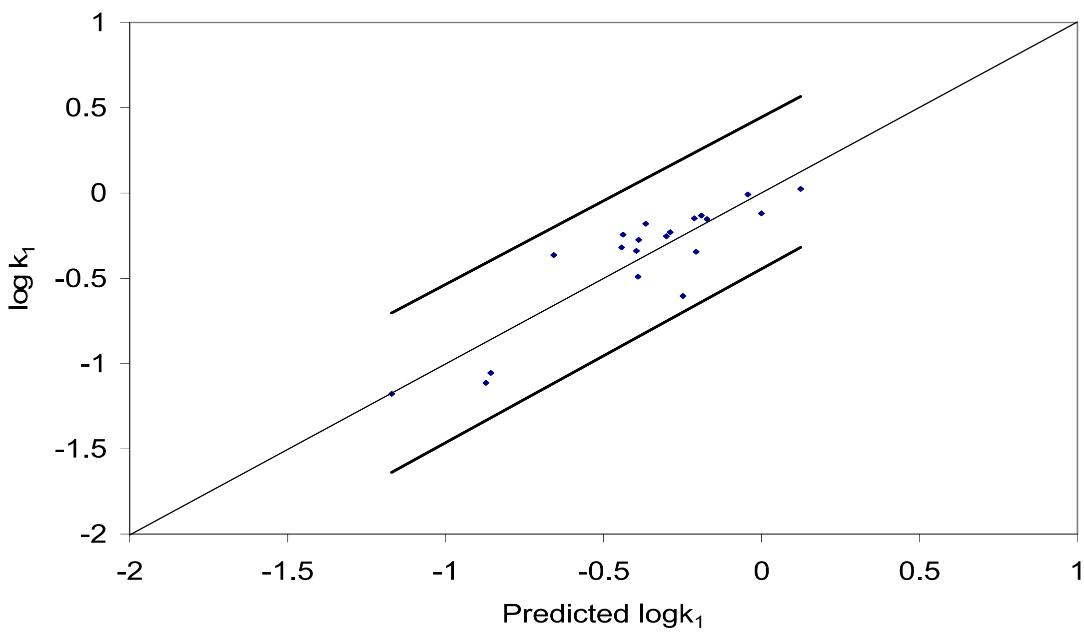


Figure 63. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all reconstituted soils for A-7-6 soils

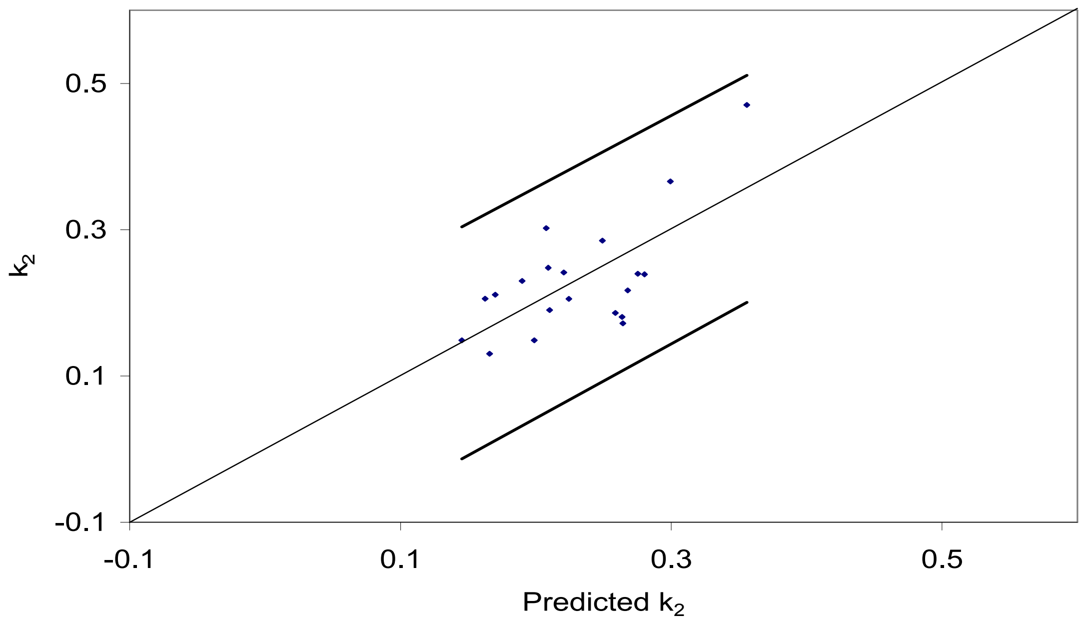


Figure 64. k_2 vs. Predicted k_2 with 95% confidence interval line for all reconstituted soils for A-7-6 soils

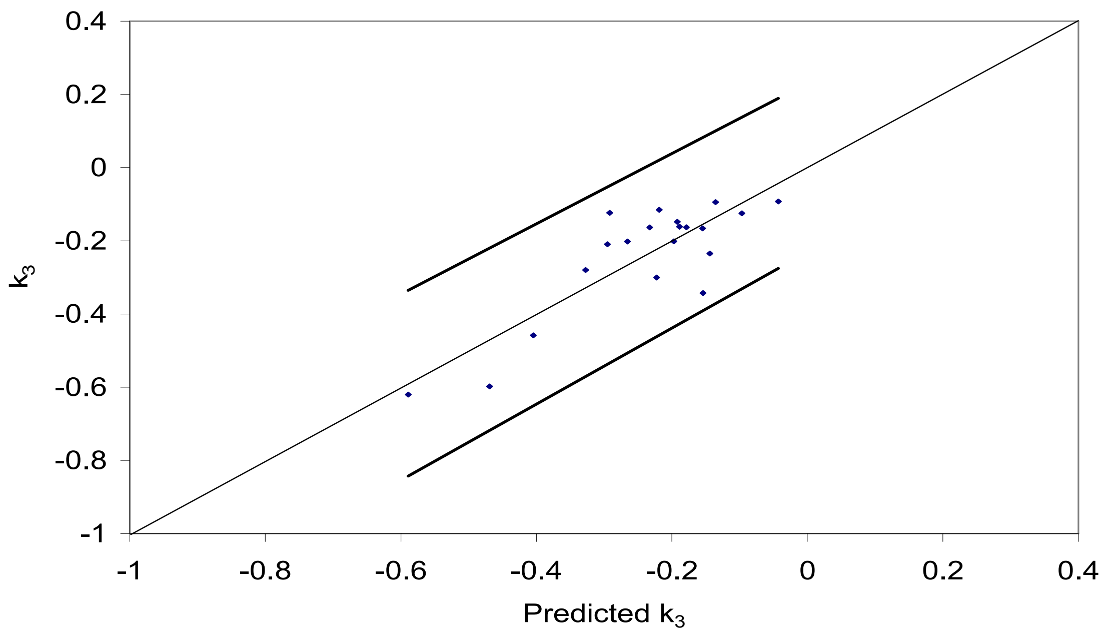


Figure 65. k_3 vs. Predicted k_3 with 95% confidence interval line for all reconstituted soils for A-7-6 soils

The M_R values now can be predicted by substituting the corresponding values of physical properties of soils in of Eqs. (53), (54), and (55) to determine k-values and then substituting these values of k coefficients into Eq. (5). The plot for predicted M_R versus laboratory M_R has been shown in Figure 66. Detail numerical values of laboratory and predicted M_R values can be found in Table C.6, Appendix C. The analysis of laboratory and predicted M_R showed that 36.33 % of predicted M_R values were within ± 10% of the laboratory M_R values and 66.33 % of predicted M_R values were within ± 20% of the laboratory M_R values.

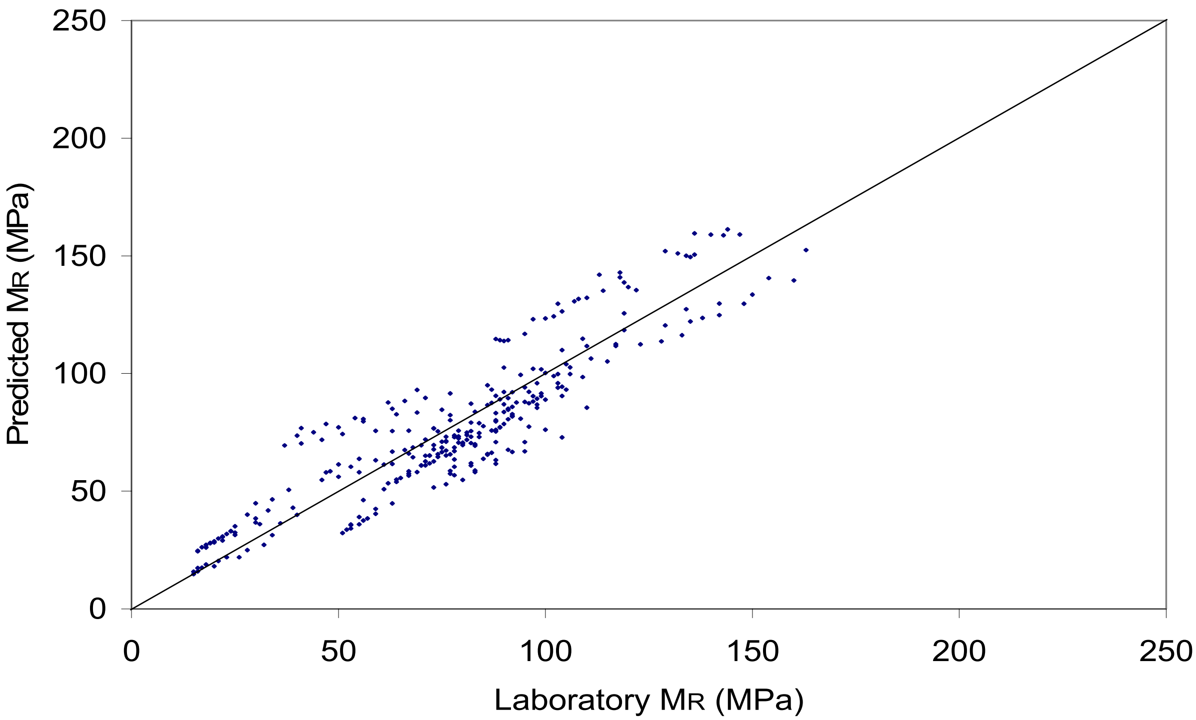


Figure 66. Predicted M_R vs. Laboratory M_R for all reconstituted samples for A-7-6 soils

- **Samples compacted at optimum moisture content:**

Regression equations developed for the k coefficients for the 13 samples from 7 different states compacted at optimum moisture content have been presented below (Eqs. (56), (57), and (58)).

$$\log k_1 = 4.52887 + 0.05361 \times OMC + 0.00223 \times DD - 7.51558 \times DDR - 0.01658 \times SN4 - 0.01507 \times CLAY \quad (R^2 = 0.82;\ Adj.\ R^2 = 0.70) \qquad (56)$$

$$k_2 = -1.25242 + 0.01445 \times OMC + 0.00092437 \times MAXDD - 0.00610 \times FSAND - 0.00825 \times CLAY \quad (R^2 = 0.80;\ Adj.\ R^2 = 0.70) \qquad (57)$$

$$k_3 = 1.12933 + 0.02765 \times OMC + 0.00104 \times DD - 3.32254 \times DDR - 0.00902 \times CLAY \quad (R^2 = 0.62;\ Adj.\ R^2 = 0.43) \qquad (58)$$

Plot for predicted M_R calculated by substituting the values of k coefficients obtained by putting the values of the soil physical properties in Eqs. (56), (57), and (58) into Eq. (5) and laboratory M_R has been presented in Figure 67. Numerical values of the predicted k coefficients can be found in Table D.18, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.6, Appendix C. The analysis of laboratory and predicted M_R showed that 67.18 % of predicted M_R values were within ± 10% of the laboratory M_R values and 95.38 % of predicted M_R values were within ± 20% of the laboratory M_R values.

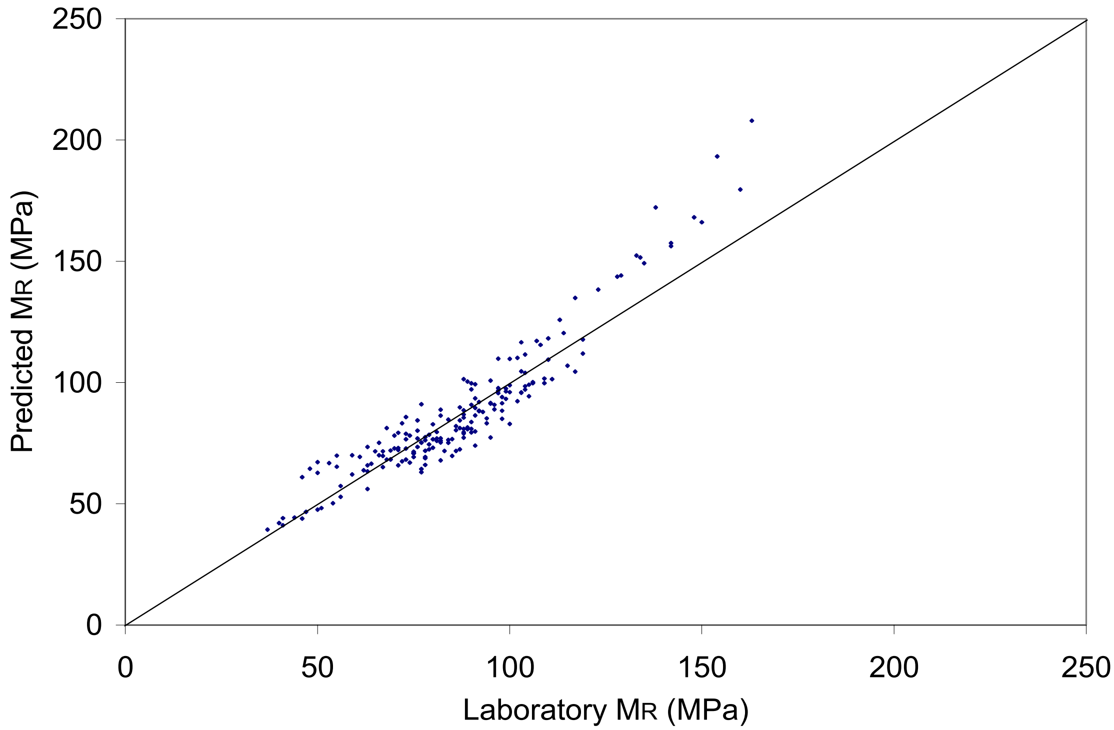


Figure 67. Predicted M_R vs. Laboratory M_R for samples compacted at optimum moisture content for A-7-6 soils

- **Samples compacted at insitu moisture content:**

Six more A-7-6 samples from Kentucky, Tennessee and Virginia were analyzed to have sufficient number of data for regression. But only 1 data could be used for the second step regression because, 2 samples resulted in R^2 less than 0.90, 2 samples had positive k_3 and 1 sample had negative k_2. Prediction models for the 8 A-7-6 soil samples compacted at insitu moisture content obtained after second step regression has been given below (Eqs. (59), (60), and (61)).

$$\log k_1 = 12.86818 - 0.27015 \times OMC - 0.00832 \times MAXDD + 6.33948 \times DDR - 0.06940 \times PL + 0.01049 \times SN200 \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \quad (59)$$

$$k_2 = 2.66267 - 0.75875 \times MCR - 0.00181 \times DD + 0.00152 \times MAXDD + 0.03833 \times PL - 0.02020 \times SN10 \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \quad (60)$$

$$k_3 = -67.73641 + 0.03590 \times MC + 4.17378 \times DDR + 0.63629 \times S1\_HALF - 0.00973 \times SN200 - 0.04721 \times CSAND \quad (R^2 = 0.99;\ Adj.\ R^2 = 0.99) \quad (61)$$

The plot for predicted M_R values, obtained by substituting k coefficients from Eqs. (59), (60), and (61) into Eq. (5), against laboratory determined M_R values has been shown in Figure 68. Numerical values of the predicted k coefficients can be found in Table D.18, Appendix D and numerical values for laboratory and predicted M_R can be found in Table C.6, Appendix C. The analysis of laboratory and predicted M_R showed that 95.83 % of predicted M_R values were within

± 10% of the laboratory M_R values and 100 % of predicted M_R values were within ± 20% of the laboratory M_R values.

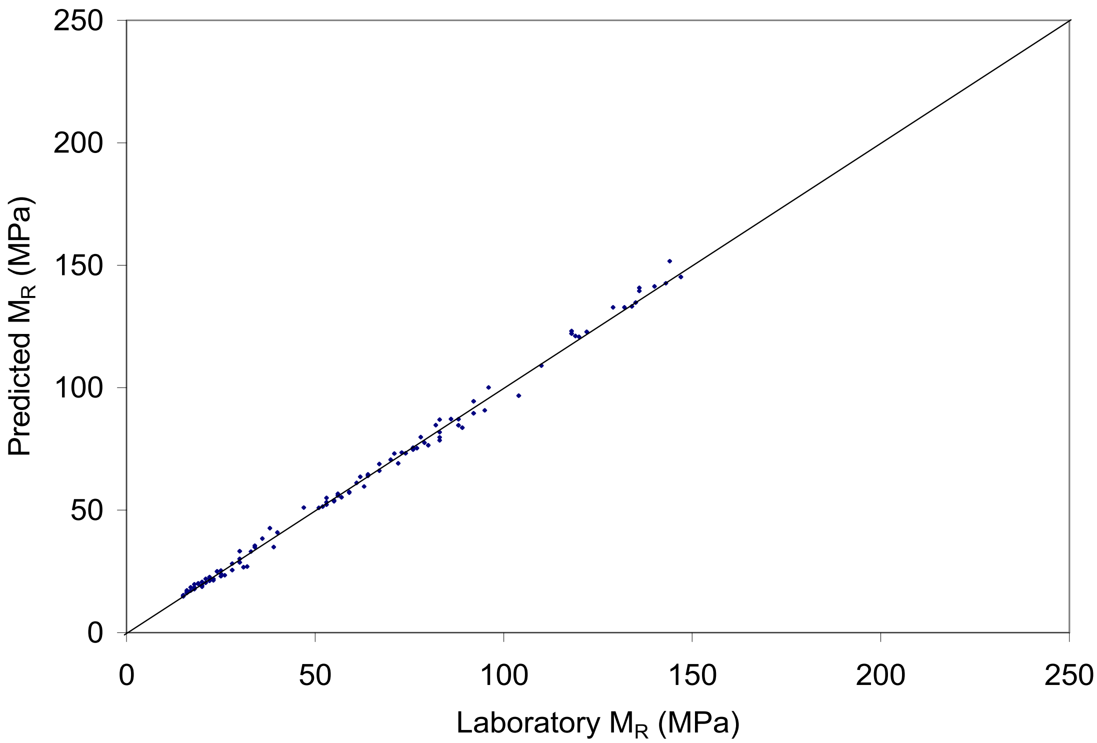


Figure 68. Predicted M_R vs. Laboratory M_R for samples compacted at insitu moisture content for A-7-6 soils

4.4 Limits of Soil Properties Values used in Second Step Regression Analysis for AASHTO Soil Types

A regression model is simply a fit to a database of observed responses. Hence, it should not be trusted to make predictions outside the range of the predictor/regressor variables used in fitting the model. Therefore, the first step in predicting values from regression model should be to verify that the prediction does not require extrapolation beyond the range of the regressor variables in the original data set (Rauch 1997). Attempting to use a regression equation beyond the range of the regressor variables is often inappropriate and may yield incredible answers (www.state.yale.edu).

The minimum and maximum of the soil properties values used in the second step regression analysis have been presented in Table 16. Designations MODEL1, MODEL2, and MODEL3 have been used for model containing all reconstituted samples, model containing samples compacted near to optimum moisture content only, and model containing samples compacted near to insitu moisture content only respectively.

Table 16. Limits of soil properties values used in second step regression analysis for AASHTO soil types

AASHTO Class.	MODEL #	Limits	LL	PL	MC, %	OMC, %	MCR, %	DD, kg/cum	MaxDD, kg/cum	DDR	S3	S2	S1_ HALF	S1
A-1-b	MODEL1	Minimum	0	0	2.8	3	0.346	1674.6	1810	0.889	91	91	88	83
		Maximum	26	24	13	13	1.2	2086.1	2226.6	1.066	100	100	100	100
	MODEL2	Minimum	0	0	2.8	3	0.933	1674.6	1810	0.925	100	100	98	95
		Maximum	0	0	13	13	1.033	2016.1	2130.4	0.972	100	100	100	100
	MODEL3	Minimum	0	0	4.2	6	0.346	1762	1858.1	0.889	91	91	88	83
		Maximum	26	24	10.5	13	1.2	2086.1	2226.6	1.066	100	100	100	100
A-3	MODEL1	Minimum	0	0	5.6	6	0.509	1569.8	1665.9	0.891	89	88	85	84
		Maximum	0	0	15.2	15	1.042	1883.8	2002.3	1.035	100	100	100	100
	MODEL2	Minimum	0	0	6.2	6	0.958	1569.8	1665.9	0.891	100	100	97	97
		Maximum	0	0	15.2	15	1.042	1840.5	1938.2	0.977	100	100	100	100
	MODEL3	Minimum	0	0	5.6	10	0.509	1804.6	1794	0.941	89	88	85	84
		Maximum	0	0	8.4	11	0.84	1883.8	2002.3	1.035	100	100	100	100
A-2-4	MODEL1	Minimum	0	0	4.5	7	0.346	1691.6	1713.9	0.877	87	75	71	67
		Maximum	27	20	14.7	13	1.456	2141.4	2194.5	1.073	100	100	100	100
	MODEL2	Minimum	0	0	8.1	8	0.9	1691.6	1778	0.877	95	92	90	88
		Maximum	27	19	12.5	13	1.078	2016.7	2114.4	1.009	100	100	100	100
	MODEL3	Minimum	0	0	4.5	7	0.346	1696.4	1713.9	0.887	87	75	71	67
		Maximum	25	20	14.7	13	1.456	2141.4	2194.5	1.073	100	100	100	100
A-4	MODEL1	Minimum	0	0	6.6	7	0.781	1422.5	1569.8	0.867	86	86	85	83
		Maximum	37	23	18.2	21	1.308	2098.3	2210.5	1.077	100	100	100	100
	MODEL2	Minimum	0	0	6.6	7	0.943	1595.1	1665.9	0.937	86	86	85	83
		Maximum	37	23	17.3	17	1.05	2098.3	2210.5	0.992	100	100	100	100
	MODEL3	Minimum	0	0	8.9	10	0.781	1422.5	1569.8	0.867	100	98	98	96
		Maximum	31	23	18.2	21	1.308	2017.8	2066.3	1.077	100	100	100	100
A-6	MODEL1	Minimum	24	13	8.9	10	0.809	1517.3	1601.8	0.934	100	93	85	84
		Maximum	40	22	22.8	21	1.175	2092.2	2018.3	1.066	100	100	100	100
	MODEL2	Minimum	24	13	10.1	10	0.962	1517.3	1601.8	0.934	100	93	85	84
		Maximum	40	21	21.3	21	1.033	1911.3	2018.3	0.966	100	100	100	100
	MODEL3	Minimum	26	14	8.9	11	0.809	1530.2	1601.8	0.951	100	100	99	90
		Maximum	40	22	22.8	21	1.175	2092.2	1986.2	1.066	100	100	100	100

Table 16. Limits of soil properties values used in second step regression analysis for AASHTO soil types *(Cont'd…)*

AASHTO Class.	MODEL #	Limits	S3_4	S1_2	S3_8	SN4	SN10	SN40	SN80	SN200	CSAND	FSAND	SILT	CLAY
A-1-b	MODEL1	Minimum	76	67	61	50	41	26	3	1.4	6	10	0.6	0
		Maximum	100	100	99	98	95	72	38	26.4	48	69	17.6	8.6
	MODEL2	Minimum	91	78	70	57	48	26	3	1.4	6	25	0.6	0.2
		Maximum	100	100	99	98	95	49	32	21.7	46	56	14.9	4.7
	MODEL3	Minimum	76	67	61	50	41	26	7	3.8	8	10	1.3	0
		Maximum	100	100	99	97	95	72	38	26.4	48	69	17.6	8.6
A-3	MODEL1	Minimum	83	82	82	81	76	53	8	1.9	2	45	1.8	0
		Maximum	100	100	100	100	100	98	57	9.6	34	94	10	6.3
	MODEL2	Minimum	96	95	93	91	87	53	8	1.9	2	46	1.8	0
		Maximum	100	100	100	100	100	98	57	9.1	34	94	10	6.3
	MODEL3	Minimum	83	82	82	81	76	54	9	3.9	19	45	3	1.3
		Maximum	100	100	100	99	97	72	24	9.6	26	69	6.1	3.5
A-2-4	MODEL1	Minimum	63	57	53	47	40	33	19	5.5	2	4	3.8	1.6
		Maximum	100	100	100	100	100	98	75	34.7	28	85	29.8	24.6
	MODEL2	Minimum	86	82	77	66	55	47	28	10.6	3	19	3.8	1.6
		Maximum	100	100	100	100	100	97	63	34.7	28	81	29.8	20.9
	MODEL3	Minimum	63	57	53	47	40	33	19	5.5	2	4	4.7	2.3
		Maximum	100	100	100	100	100	98	75	33.8	24	85	24.6	24.6
A-4	MODEL1	Minimum	80	76	74	69	60	48	42	35.2	0	1	21.5	2.8
		Maximum	100	100	100	100	100	99	99	98	36	57	87.2	32.2
	MODEL2	Minimum	80	76	74	69	60	48	42	35.2	0	1	21.5	2.8
		Maximum	100	100	100	100	100	98	98	96.6	18	57	85.2	31.5
	MODEL3	Minimum	94	90	87	83	80	62	48	40.5	0	1	25.5	2.8
		Maximum	100	100	100	100	100	99	99	98	36	50	87.2	32.2
A-6	MODEL1	Minimum	80	77	76	70	62	51	37	18.8	0	1	27.3	12.1
		Maximum	100	100	100	100	100	99	98	97.5	14	37	71.2	42.6
	MODEL2	Minimum	80	77	76	72	63	51	37	18.8	0	1	27.3	14.3
		Maximum	100	100	100	100	100	97	96	88.7	14	37	71.2	42.6
	MODEL3	Minimum	88	83	79	70	62	53	48	43	0	1	32.3	12.1
		Maximum	100	100	100	100	100	99	98	97.5	13	30	70.3	31.1

Table 16. Limits of soil properties values used in second step regression analysis for AASHTO soil types *(Cont'd…)*

AASHTO Class.	MODEL #	Limits	LL	PL	MC, %	OMC, %	MCR, %	DD, kg/cum	MaxDD, kg/cum	DDR	S3	S2	S1_ HALF	S1
A-7-6	MODEL1	Minimum	41	15	12.9	13	0.974	1463.8	1473.7	0.888	100	97	95	93
		Maximum	68	27	30.7	27	1.289	1780.1	1810	1.029	100	100	100	100
	MODEL2	Minimum	41	15	12.9	13	0.974	1490.4	1569.8	0.929	100	97	95	93
		Maximum	68	27	22.5	22	1.028	1721.8	1810	1.002	100	100	100	100
	MODEL3	Minimum	41	17	16.6	16	1.038	1463.8	1473.7	0.888	100	100	99	98
		Maximum	57	24	30.7	27	1.335	1780.1	1729.9	1.029	100	100	100	100

Table 16. Limits of soil properties values used in second step regression analysis for AASHTO soil types *(Cont'd…)*

AASHTO Class.	MODEL #	Limits	S3_4	S1_2	S3_8	SN4	SN10	SN40	SN80	SN200	CSAND	FSAND	SILT	CLAY
A-7-6	MODEL1	Minimum	91	88	85	78	70	59	55	51	0	1	14.8	24.2
		Maximum	100	100	100	100	100	99	99	98.6	13	28	71.7	58.5
	MODEL2	Minimum	91	88	85	78	70	59	55	51.1	0	1	14.8	24.2
		Maximum	100	100	100	100	100	99	99	98.6	13	28	70.5	51.3
	MODEL3	Minimum	94	92	91	88	85	78	63	51	1	1	23.9	25.1
		Maximum	100	100	100	100	100	99	97	96.7	13	24	71.7	58.5

5. RESILIENT MODULUS OF SUBGRADES BY USCS SOIL TYPES

The data collected for the 259 undisturbed/reconstituted samples from the LTPP database (as mentioned in Section 4.3) were also classified according to Unified Soil Classification System (USCS) into Coarse Grained Soils and Fine Grained Soils (Table E.1 and E.2, Appendix E). Prediction models for the k coefficients were developed for both types of soils to estimate values of the resilient modulus. Coarse Grained soils are those which have more than 50% retained on No. 200 sieve and Fine Grained soils are those which have 50% or more passing through No. 200 sieve (Das 1999). Histogram and percentage cumulative frequency curves for the laboratory M_R values for the soils types Coarse and Fine Grained soils have been presented in Figures 69, 70, 71, and 72.

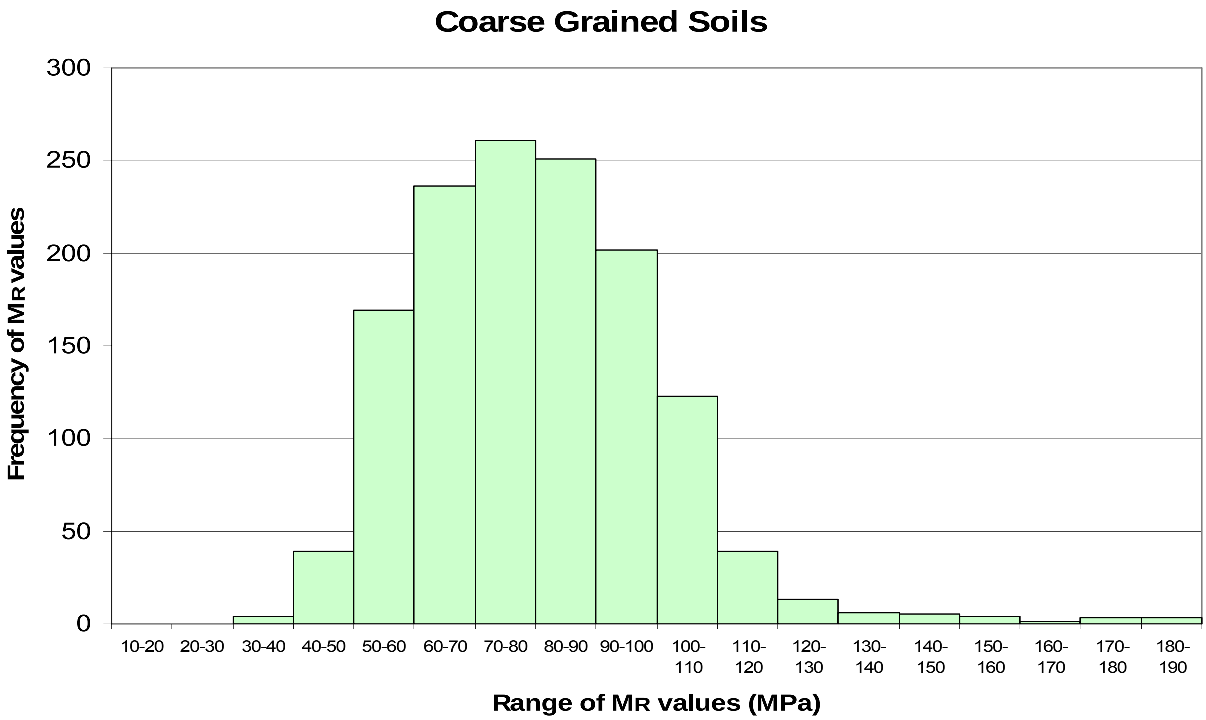


Figure 69. Histogram of laboratory M_R values for Coarse Grained Soils

5.1 Resilient Modulus Prediction Models for USCS Soil Types:

The ranges of k coefficients used in second step regression for Coarse Grained and Fine Grained have been presented in Table 17. The actual values of k coefficients for each sample can be found in Table D.1 through D.6 Appendix D. While developing k coefficient prediction models for USCS soil types, in addition to the soil properties listed in Section 4.3.2 used for AASHTO soil types, Uniformity Coefficient (CU) and Coefficient of Curvature (CC) were used for Coarse Grained soils and Plasticity Index (PI) was used for Fine Grained soils. Uniformity Coefficient (CU) is a measure of the gradation level of a granular material and is given by $CU=D_{60}/D_{10}$. Coefficient of Curvature (CC) is the measure of the shape of a grading curve and is given by $CC= (D_{30})^2/(D_{60}xD_{10})$. D_{10}, D_{30}, and D_{60} are the diameters corresponding to percents finer than 10, 30, and 60% respectively. Grain size distribution curves were plotted for all 91 coarse grained soil samples data collected from LTPP database and are reported in Figures E.1 (Appendix E). Based on these curves, CU and CC values were calculated for each sample which can be found in Table E.1.

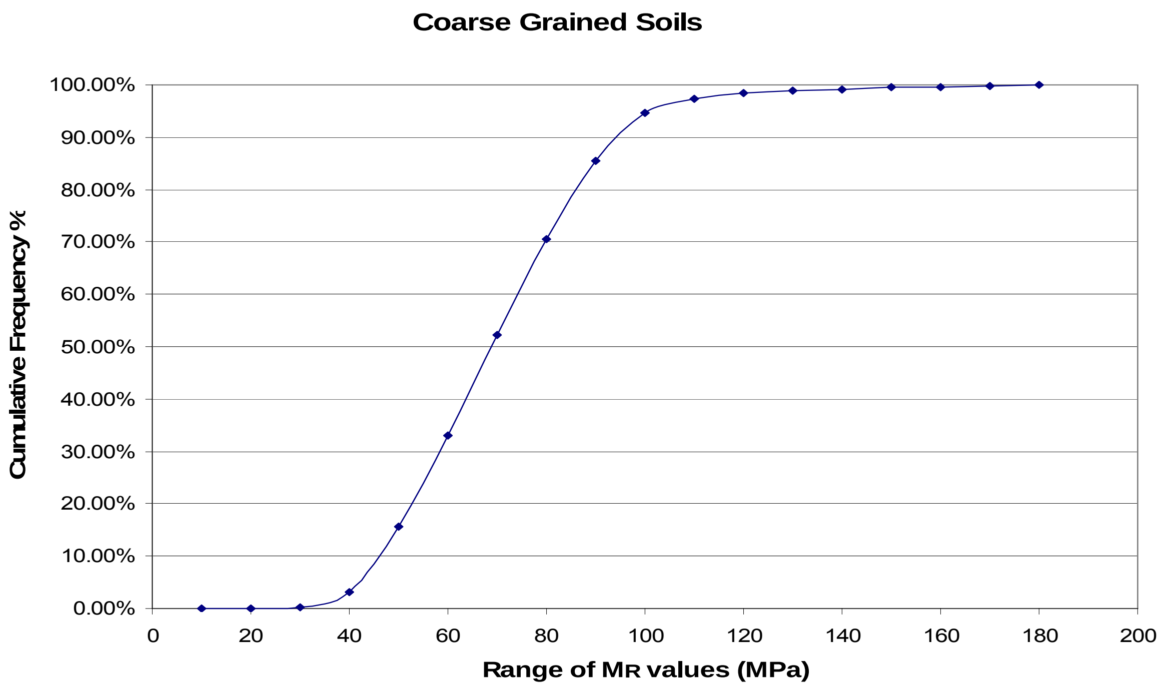


Figure 70. Percentage cumulative frequency curve for Coarse Grained Soils

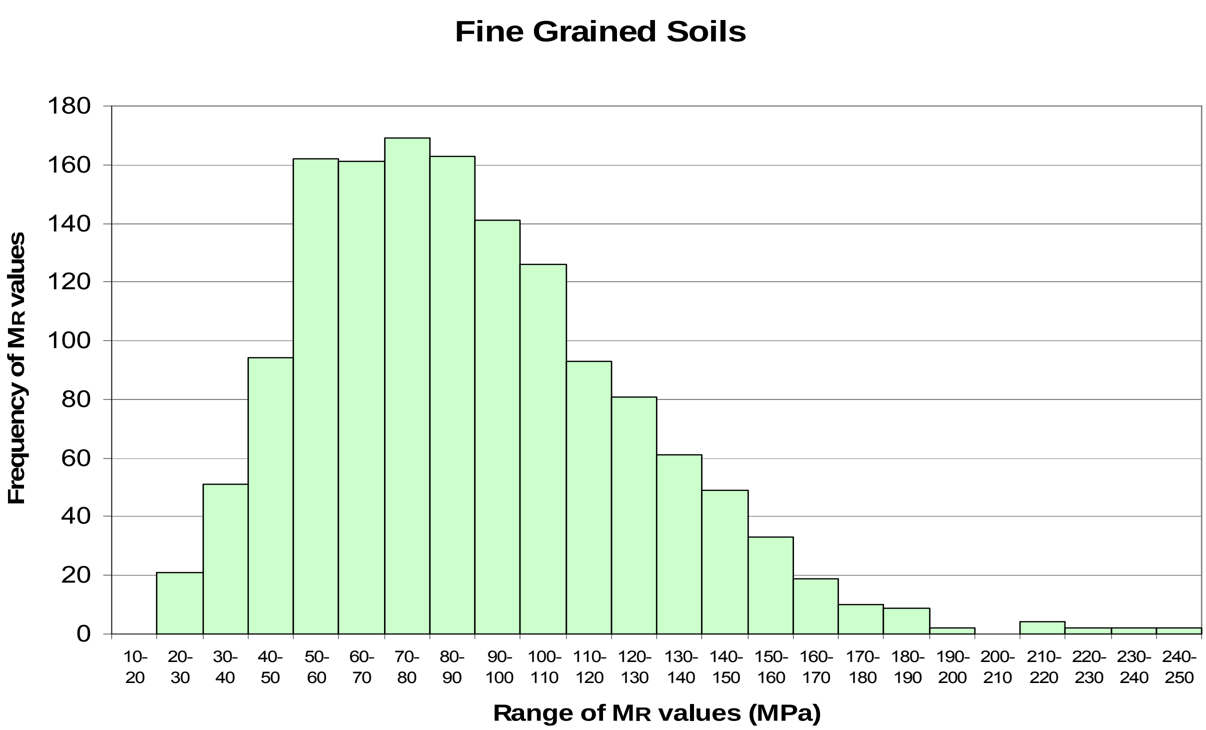


Figure 71 . Histogram of laboratory M_R values for Fine Grained Soils

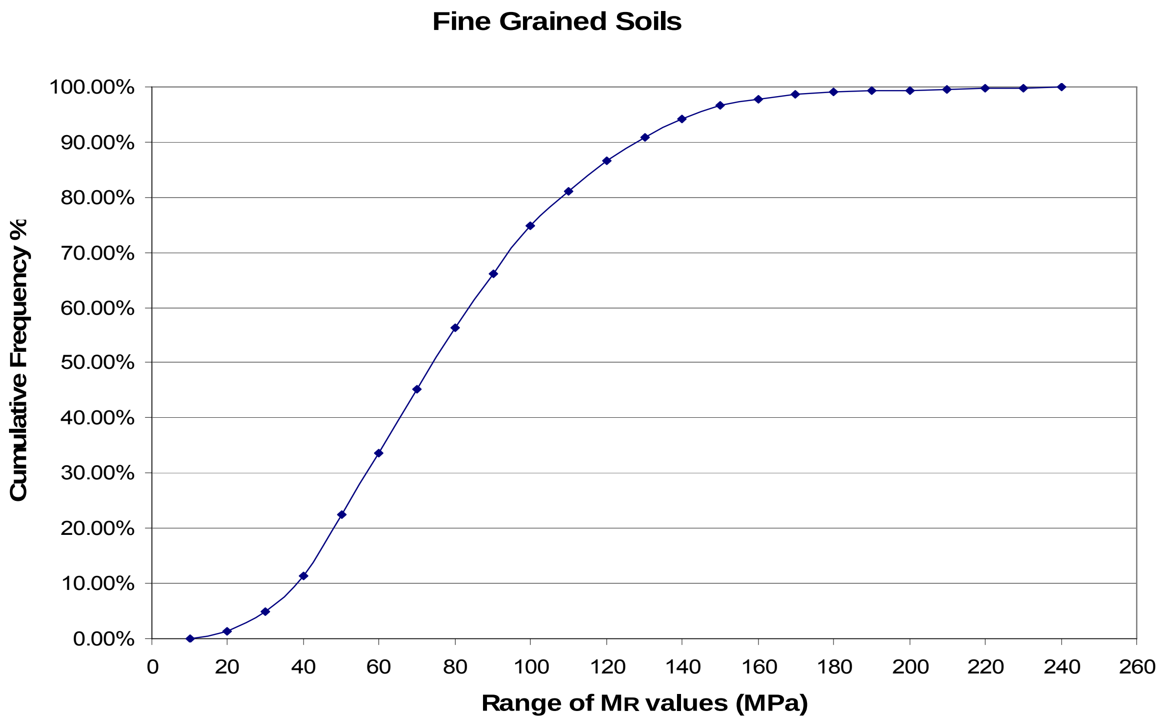


Figure 72. Percentage cumulative frequency curve for Fine Grained Soils

Table 17. Range of k coefficients for Coarse Grained and Fine Grained soils used in second step regression

USCS Soil Type	Variable	No. of Samples	Mean	Standard Deviation	Minimum	Maximum
Coarse Grained (All Samples)	k_1	91	0.46610	0.10443	0.21628	1.01422
	k_2	91	0.65136	0.11869	0.28572	0.88301
	k_3	91	-0.16708	0.08480	-0.41500	-0.00894
Coarse Grained (Samples with CU≤100 only)	k_1	74	0.46977	0.08053	0.21628	0.68305
	k_2	74	0.67972	0.09555	0.45572	0.88301
	k_3	74	-0.14326	0.06356	-0.41500	-0.00894
Fine Grained	k_1	97	0.48174	0.30195	0.06643	1.53817
	k_2	97	0.33366	0.14950	0.13053	0.98855
	k_3	97	-0.29013	0.13991	-0.62807	-0.03903

5.1.1 USCS Soil Type: Coarse Grained

Ninety one soil samples were available for second step regression for the coarse grained soils after screening for samples with R^2 less than 0.90, samples with negative k_1 and k_2 and positive k_3. It can be observed from the histogram of CU values (Figure 73) that the majority (81.3%) of coarse grained soils had Uniformity Coefficient (CU) values less than 100. Therefore, two sets of models have been developed for coarse grained soils. The first set of model has all samples extracted from the LTPP database that fall in coarse grained criteria. The second set of model were developed incorporating only those soil samples which had CU≤100 to avoid possible influence of some extreme values of CU on the prediction models. Histogram of CU values for coarse grained soil samples with CU≤100 has been presented in Figure 74. It can be seen from Figure 74 that the majority of samples have CU<10.

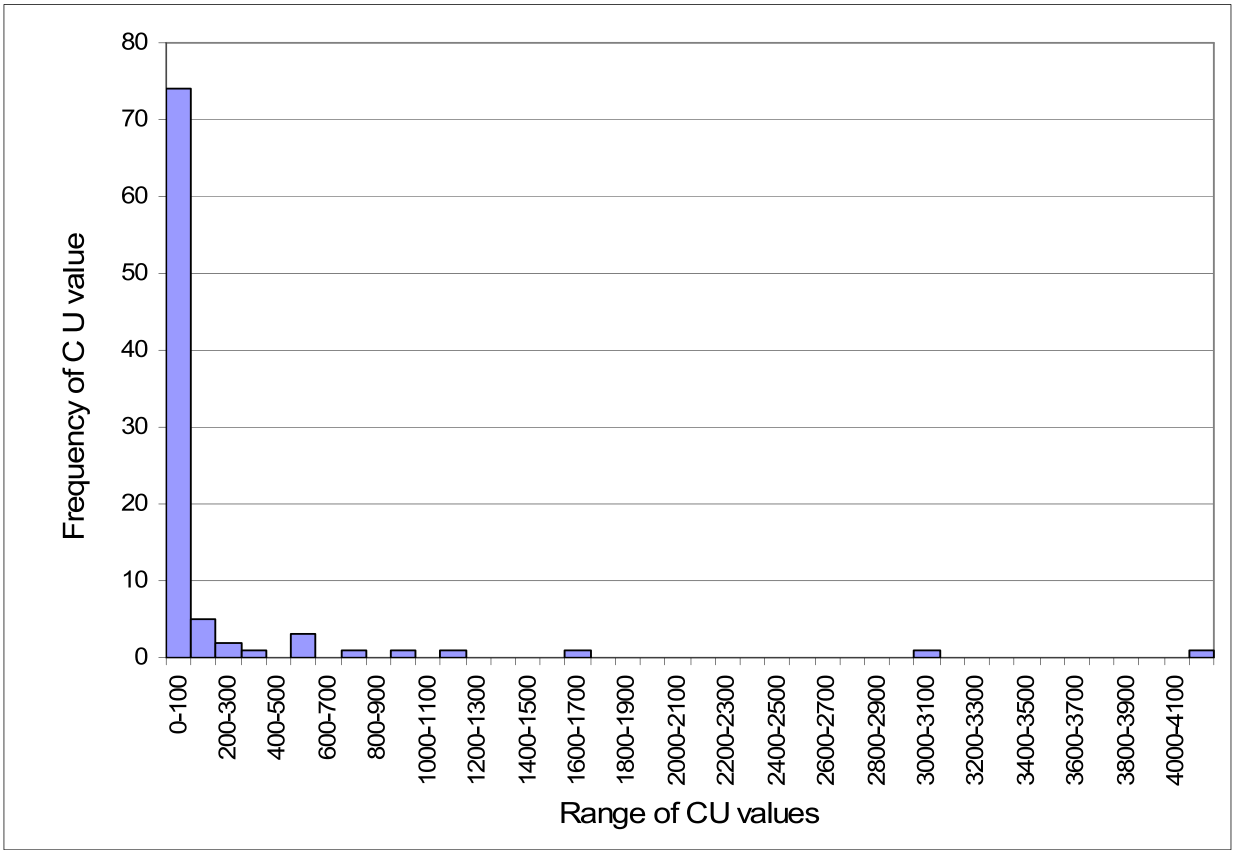


Figure 73. Histogram of CU values for all Coarse Grained Soils

- **All Coarse Grained samples:**

Regression equations developed for k coefficients from 91 coarse grained soils have been presented below along with the R^2 values for each equation.

log k1 = -1.77341 + 0.00017562 x MAXDD + 0.02707 x S3 - 0.02043 x S1 + 0.00501 x S3_8 - 0.00819 x SN200 + 0.00501 x SILT (R^2 = 0.40; Adj. R^2 = 0.36) (62)

k2 = -0.49426 + 0.11250 x MCR + 0.00026190 x DD + 0.00592 x S3 - 0.00398 x SN40 + 0.00479 x FSAND - 0.00006099 x CU - 0.0000967 x CC (R^2 = 0.45; Adj. R^2 = 0.41) (63)

k3 = -0.44082 - 0.00232 x MC + 0.00021026 x MAXDD - 0.00531 x S1_2 + 0.00561 x SN10 - 0.00529 x SN200 (R^2 = 0.63; Adj. R^2 = 0.61) (64)

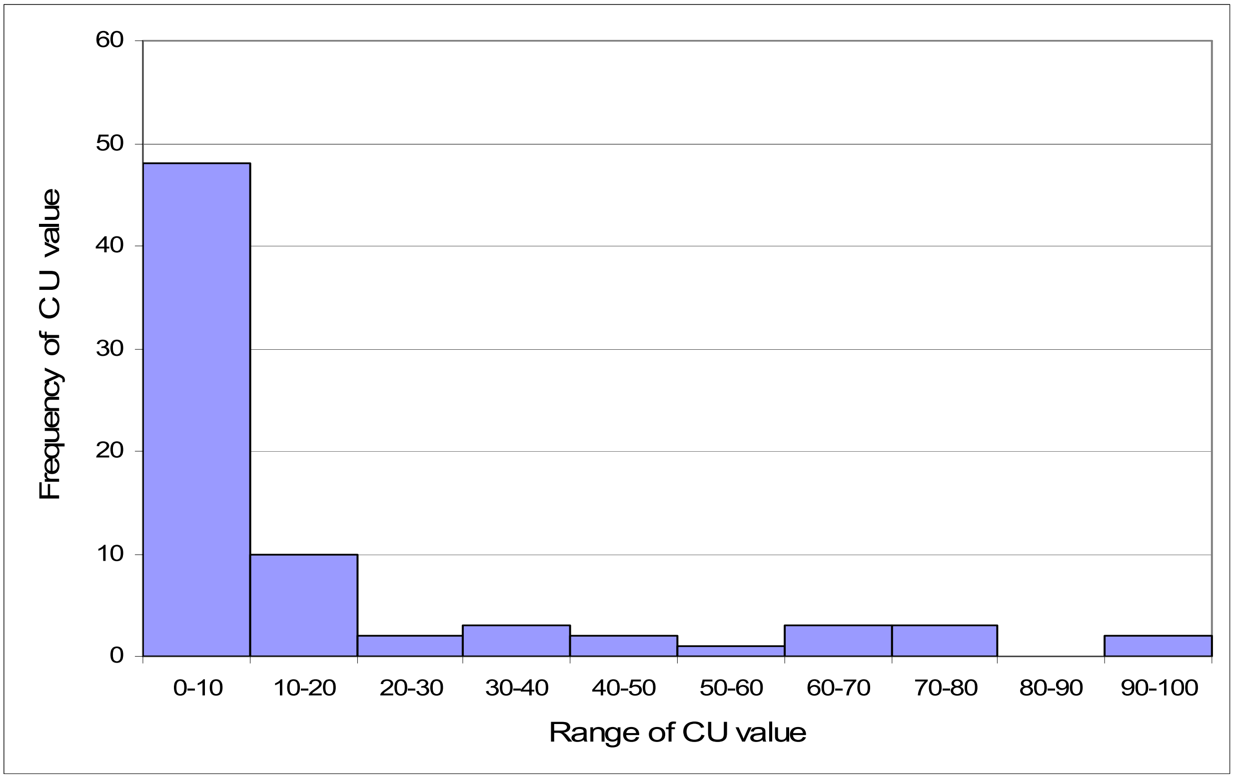


Figure 74. Histogram of CU values for Coarse Grained Soils with CU≤100

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (62), (63), and (64) along with 95% confidence interval lines has been presented in Figure 75, 76, and 77. Numerical values of the predicted k coefficients can be found in Table F.1, Appendix F.

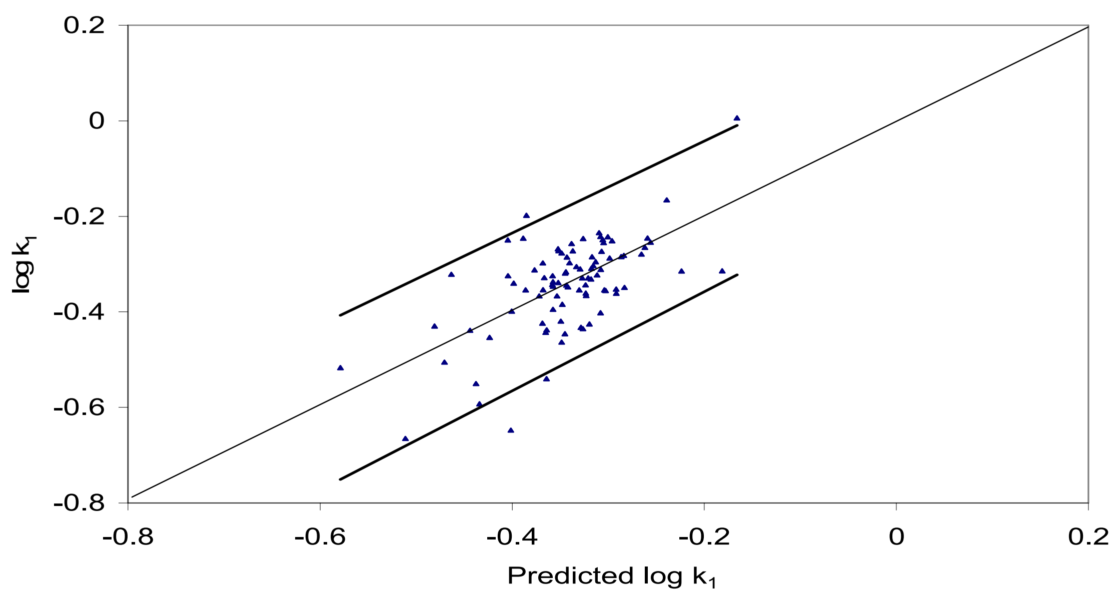


Figure 75. log k_1 vs. Predicted log k_1 with 95% confidence interval line for all Coarse Grained soils

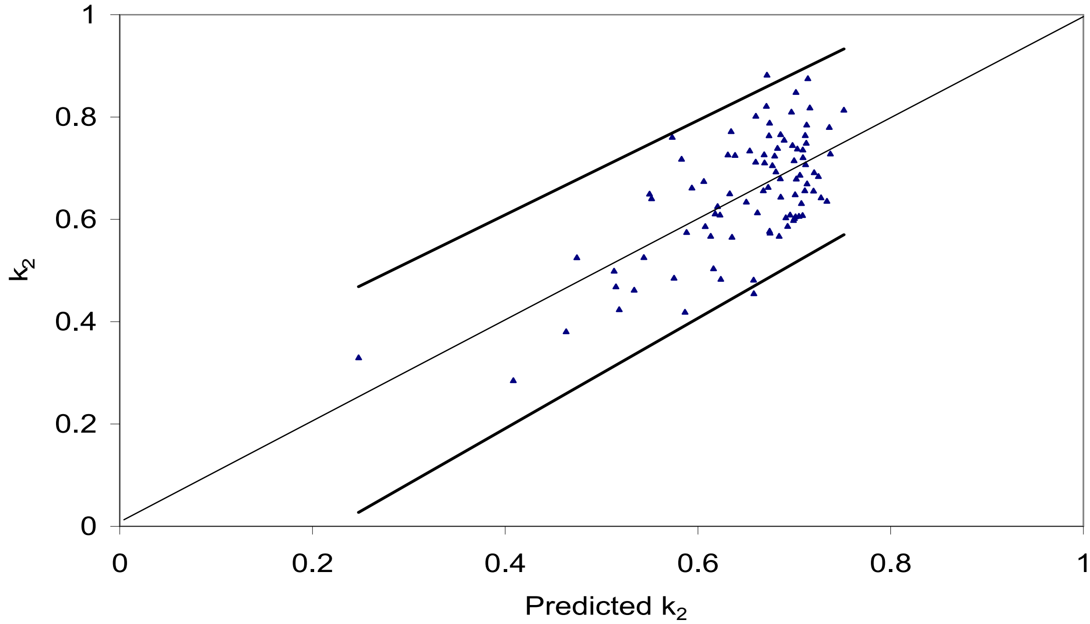


Figure 76. k_2 vs. Predicted k_2 with 95% confidence interval line for all Coarse Grained soils

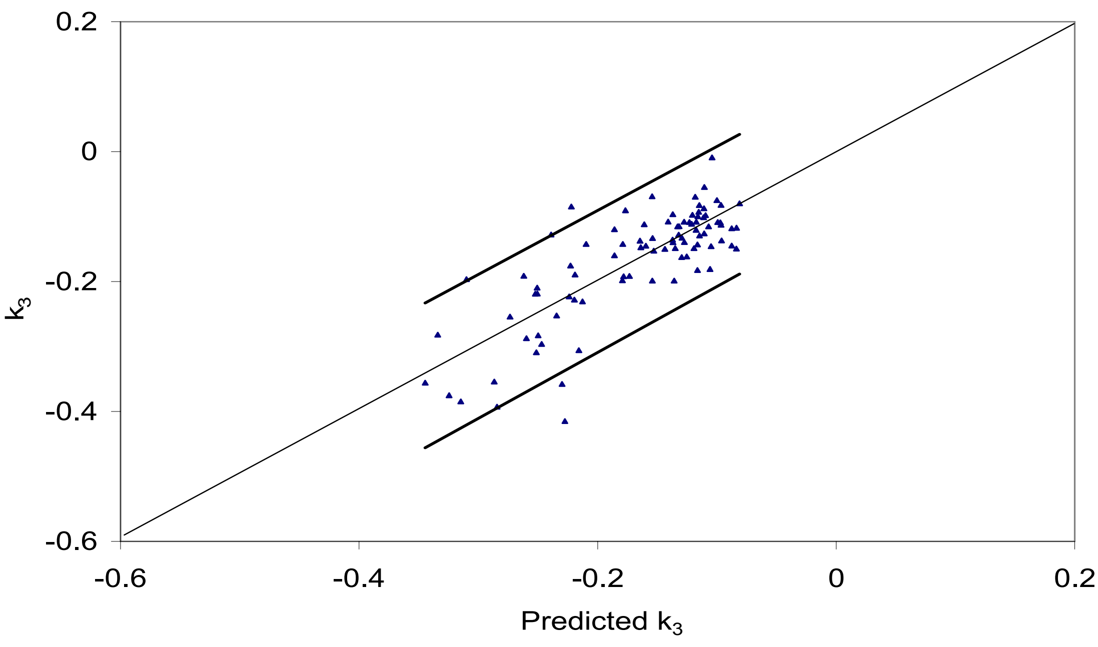


Figure 77. k_3 vs. Predicted k_3 with 95% confidence interval line for all Coarse Grained soils

Plot for predicted M_R calculated by substituting values of k_1, k_2, and k_3 obtained from Eqs. (62), (63), and (64) into Eq. (5) against laboratory M_R has been presented in Figure 78. Numerical values of laboratory and predicted M_R can be found in Table F.3, Appendix F. Analysis of predicted and laboratory M_R values showed that 50.04% and 77.63% of predicted M_R were within ± 10% and ± 20% respectively, of laboratory M_R.

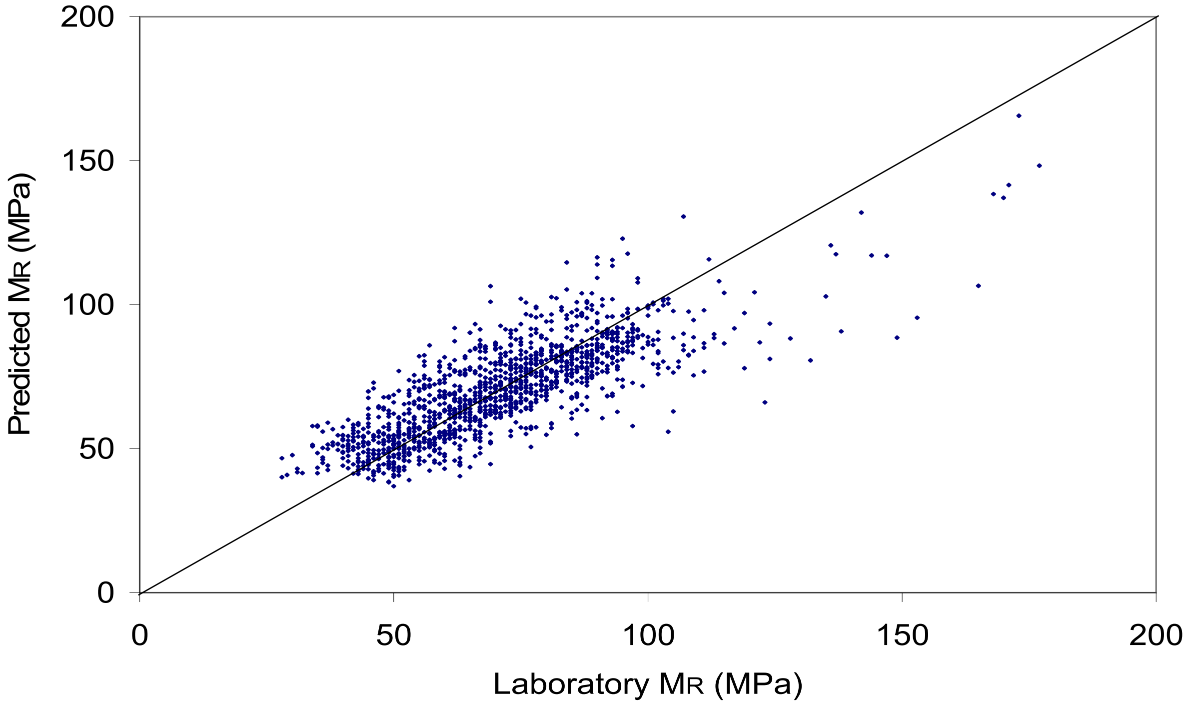


Figure 78. Predicted M_R vs. Laboratory M_R for all Coarse Grained soils

- **Coarse Grained samples with CU≤100:**

Prediction models for k coefficients developed from 74 coarse grained soil samples that had CU≤100 have been presented in Eqs. (65), (66), and (67).

$$\log k_1 = 0.61689 - 0.00815 \times OMC - 0.06144 \times MCR - 0.80003 \times DDR - 0.00878 \times SN200 + 0.00624 \times SILT + 0.00621 \times CLAY - 0.00502 \times CC \quad (R^2 = 0.47; \text{Adj. } R^2 = 0.41) \quad (65)$$

$$k_2 = 0.43372 + 0.00687 \times MC + 0.00039979 \times DD - 0.00026666 \times MAXDD - 0.00331 \times SN40 + 0.00297 \times FSAND + 0.00515 \times CC \quad (R^2 = 0.22; \text{Adj. } R^2 = 0.15) \quad (66)$$

$$k_3 = 0.51731 - 0.00390 \times MC - 0.43830 \times DDR - 0.00594 \times S1\_2 + 0.00509 \times SN10 - 0.00070032 \times SN40 - 0.00418 \times SN200 + 0.00441 \times CLAY \quad (R^2 = 0.52; \text{Adj. } R^2 = 0.47) \quad (67)$$

Numerical values of predicted k coefficients can be found in Table F.1, Appendix F and numerical values of laboratory and predicted M_R can be found in Table F.3, Appendix F. Plot for predicted M_R versus laboratory M_R has been presented in Figure 79. The analysis of predicted and laboratory M_R showed that 60.32% and 85.75% of predicted M_R values were within ±10% and ± 20% respectively, of the laboratory M_R values.

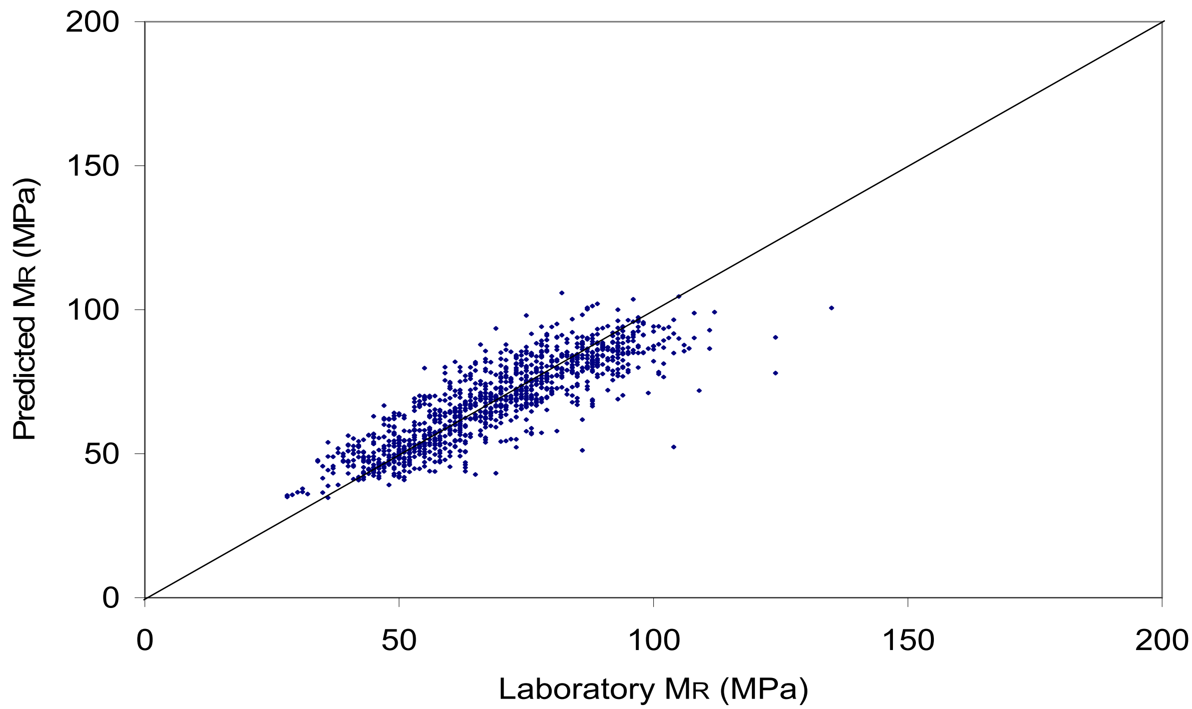


Figure 79. Predicted M_R vs. Laboratory M_R for Coarse Grained soils with CU≤100

5.1.2 USCS Soil Type: Fine Grained

Ninety seven soil samples were available to carry out second step regression for the fine grained soils after removing samples with R^2<0.90 and samples with negative values of k_1 and k_2 and positive value of k_3. Prediction models developed for k coefficients have been presented below.

$$\log k_1 = 6.99969 - 0.11144 \times OMC - 1.15320 \times MCR - 0.00154 \times MAXDD + 0.01875 \times PI - 0.02339 \times S1 + 0.00445 \times SN200 \quad (R^2 = 0.41; \text{Adj. } R^2 = 0.37) \quad (68)$$

$$k_2 = 0.55494 + 0.25904 \times MCR - 0.00651 \times PI - 0.00785 \times SN4 + 0.00712 \times SN40 - 0.00266 \times SN200 - 0.00318 \times CLAY \quad (R^2 = 0.39; \text{Adj. } R^2 = 0.34) \quad (69)$$

$$k_3 = 2.08483 - 0.03626 \times MC - 0.00044337 \times MAXDD + 0.01104 \times LL - 0.02024 \times S1 + 0.00494 \times SN80 + 0.01012 \times CSAND + 0.00392 \times FSAND + 0.00287 \times SILT \quad (R^2 = 0.33; \text{Adj. } R^2 = 0.27) \quad (70)$$

Plot for k coefficients obtained from first step regression against the predicted k coefficients determined from Eqs. (68), (69), and (70) along with 95% confidence interval lines has been presented in Figure 80, 81, and 82. Numerical values of predicted k coefficients can be found in Table F.2, Appendix F and numerical values of laboratory and predicted M_R can be found in Table F.4, Appendix F. The plot for M_R predicted using Eqs. (68), (69), and (70) against laboratory M_R has been presented in Figure 83. The analysis of laboratory and predicted M_R

showed that 30.03% of predicted M_R were within ± 10% of laboratory M_R and 50.86% of predicted M_R were within ± 20% of the laboratory M_R.

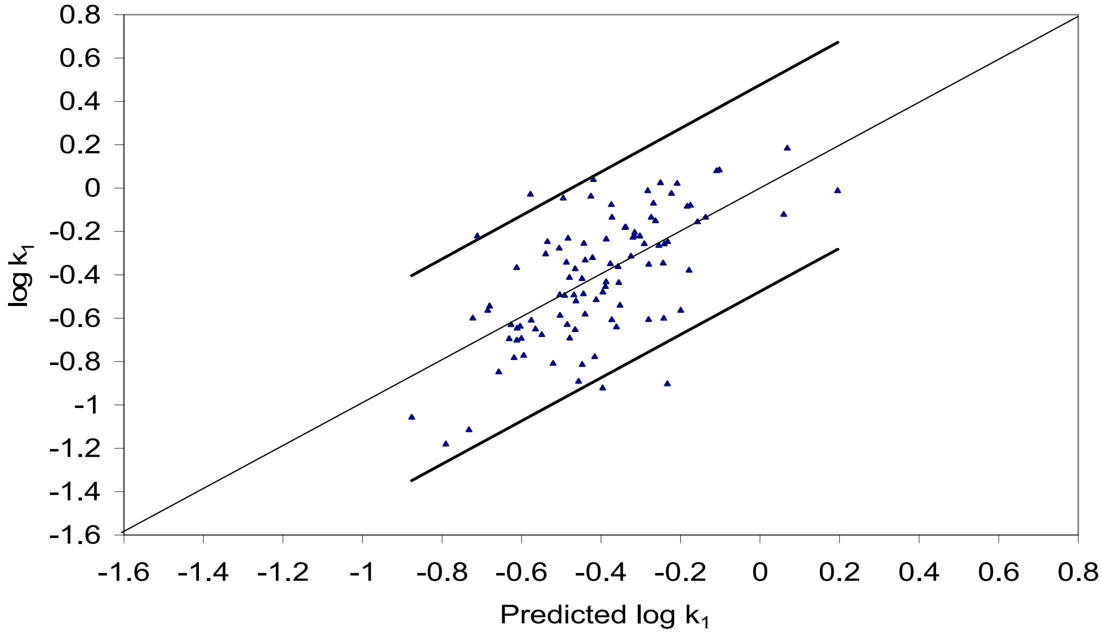


Figure 80. log k_1 vs. Predicted log k_1 with 95% confidence interval line for Fine Grained soils

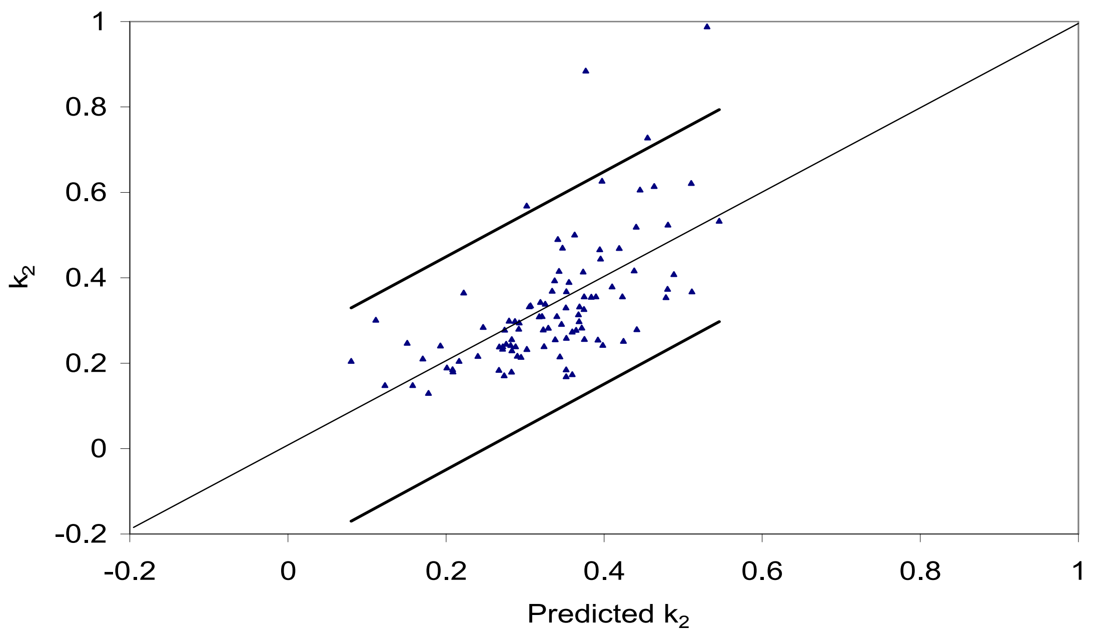


Figure 81. k_2 vs. Predicted k_2 with 95% confidence interval line for Fine Grained soils

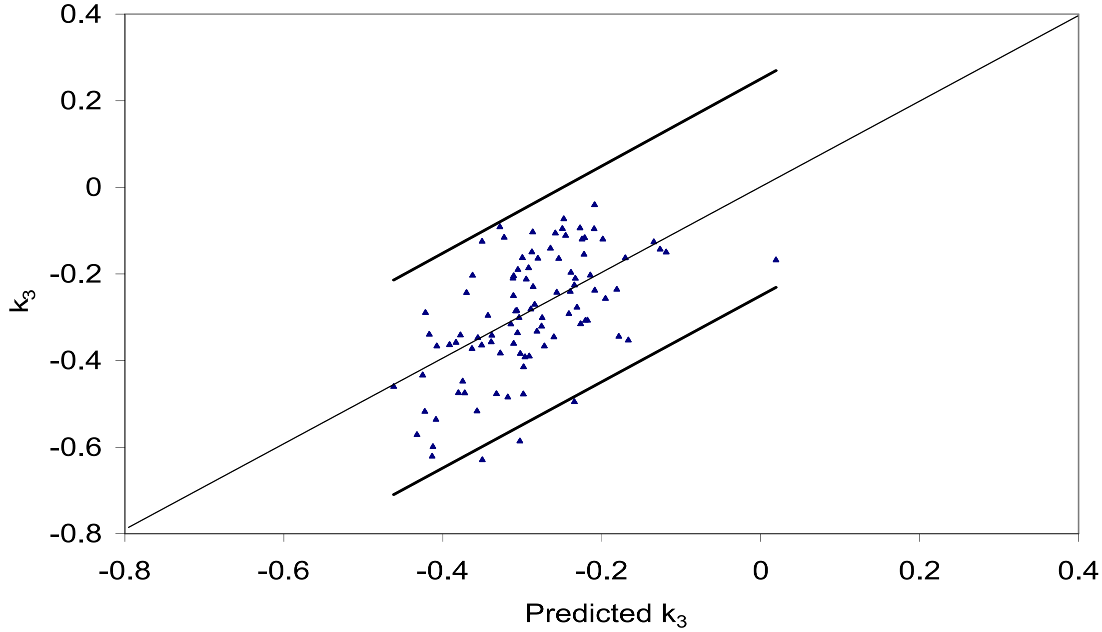


Figure 82. k_3 vs. Predicted k_3 with 95% confidence interval line for Fine Grained soils

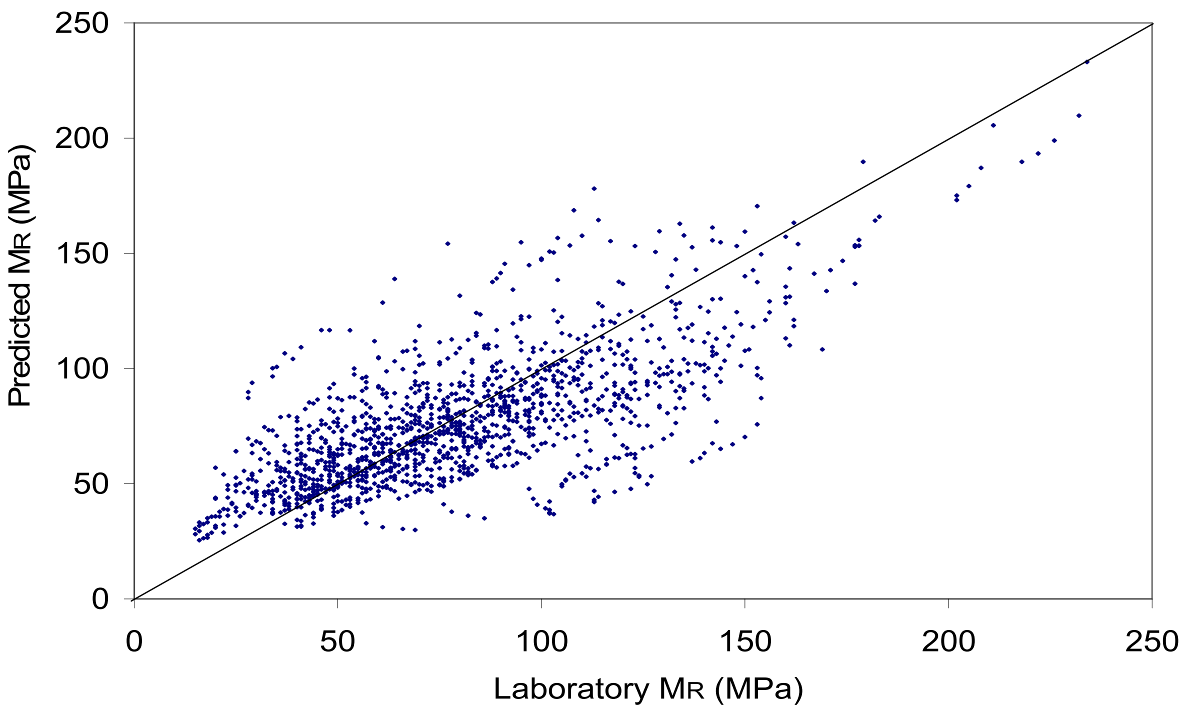


Figure 83. Predicted M_R vs. Laboratory M_R for Fine Grained soils

5.2 Limits of Soil Properties Values Used in Second Step Regression for USCS Soil Types

Regression models may not be reliable to make predictions outside the range of predictor variables used in developing the models. Therefore, values of predictors must be checked before using the prediction models. The minimum and maximum of the soil properties values used in the second step regression analysis for the USCS soil types have been presented in Table 18.

Table 18. Limits of soil properties values used in second step regression analysis for USCS soil types

USCS Class.	Limits	LL	PI	MC, %	OMC, %	MCR, %	DD, kg/cum	MaxDD, kg/cum	DDR	S3	S2	S1_ HALF	S1	S3_4
Coarse Grained (All samples)	Minimum	-	-	2.8	3	0.346	1569.8	1665.9	0.877	86	75	71	67	63
	Maximum	-	-	15.2	15	1.322	2141.4	2226.6	1.073	100	100	100	100	100
Coarse Grained (Samples with CU≤100)	Minimum	-	-	2.8	3	0.346	1569.8	1665.9	0.877	89	88	85	84	83
	Maximum	-	-	15.2	15	1.322	2141.4	2226.6	1.073	100	100	100	100	100
Fine Grained	Minimum	15	1	8.3	8	0.781	1422.5	1473.7	0.867	96	93	85	84	80
	Maximum	68	44	30.7	27	1.308	2092.2	2210.5	1.077	100	100	100	100	100

Table 18. Limits of soil properties values used in second step regression analysis for USCS soil types *(Cont'd…)*

USCS Class.	Limits	S1_2	S3_8	SN4	SN-10	SN-40	SN-80	SN-200	CSA-ND	FSA-ND	SILT	CLAY	CU	CC
Coarse Grained (All samples)	Minimum	57	53	47	40	26	3	1.4	2	4	0.6	0	1.824	0.16
	Maximum	100	100	100	100	98	75	44.8	48	94	42	12.6	4166.67	1018.95
Coarse Grained (Samples with CU≤100)	Minimum	82	80	76	71	26	3	1.4	2	21	0.6	0	1.824	0.483
	Maximum	100	100	100	100	98	75	44.8	48	94	42	9.9	100	34.857
Fine Grained	Minimum	77	76	70	62	51	37	18.8	0	1	14.8	8.6	-	-
	Maximum	100	100	100	100	99	99	98.6	19	45	87.2	58.5	-	-

6. EXPERIMENTAL VERIFICATION

In order to verify the prediction models developed in Chapters 4 and 5 for the AASHTO and USCS soil types, independent laboratory resilient modulus tests were carried out on soil samples collected in New England. The general procedure involved in laboratory test has been described in the subsequent section.

6.1 Resilient Modulus Test Procedure:

Resilient Modulus of subgrade soils can be determined by the repeated load triaxial tests in the laboratory. Figure 84 shows the typical test setup for such test as recommended by AASHTO - T 307. Air is used as the confining fluid in the triaxial chambers.

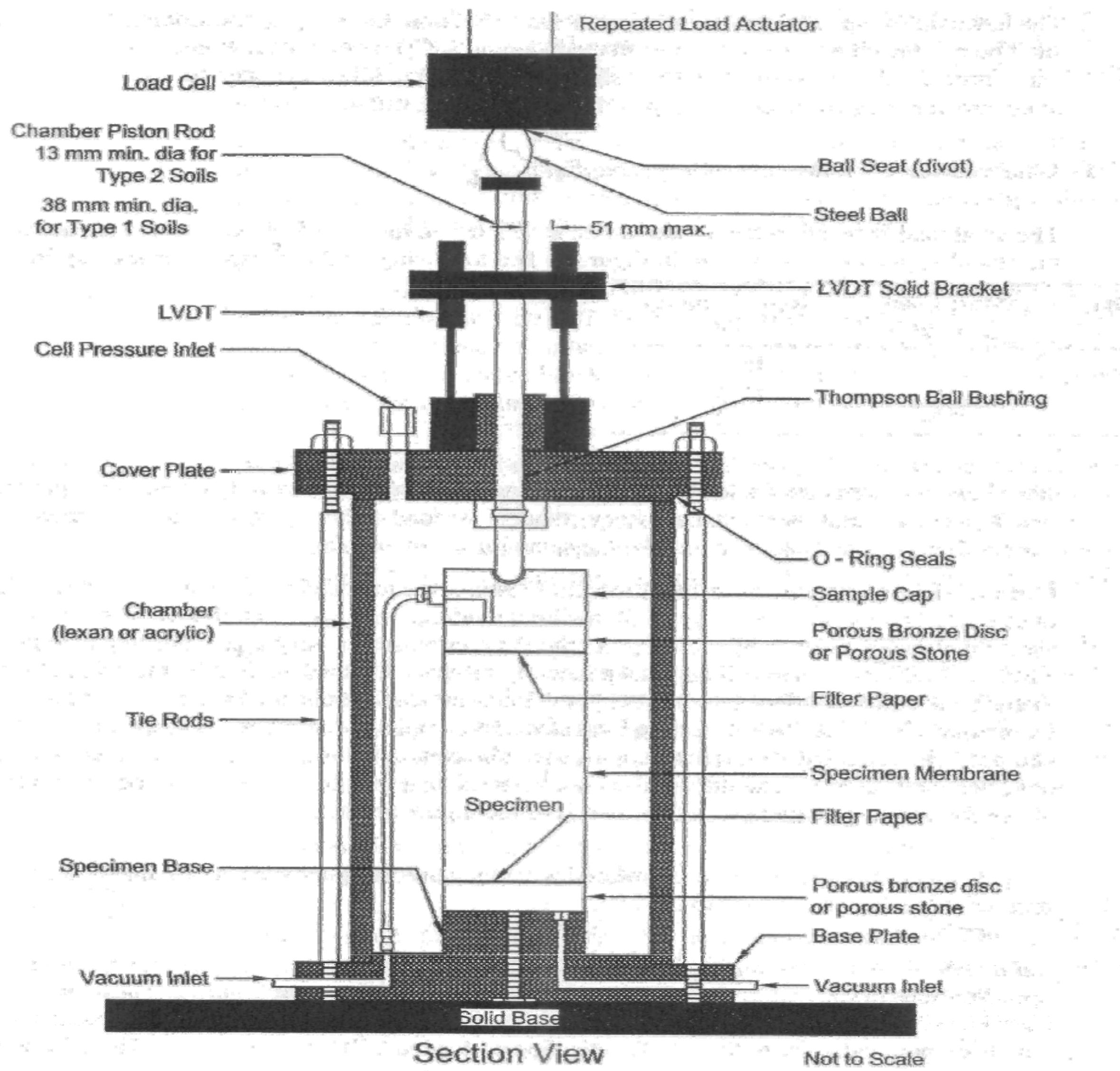


Figure 84. Typical Triaxial Chamber with External LVDTs and Load Cell (Figure from AASHTO – T 307)

A repeated axial cyclic stress (S_{cyclic}) of fixed magnitude is applied to a cylindrical test specimen using a haversine-shaped load pulse with load duration (0.1s), and cycle duration (1.0 to 3.1 s) as shown in Figure 85. The test specimen is subjected to the dynamic cyclic stress (S_{cyclic}) and a static confining stress provided by means of a triaxial pressure. For subgrade soils, each soil specimen is tested at 3 levels of confining pressure (41.4, 27.8, and 13.8 kPa). At each level of confining pressure 5 levels of cyclic stress are applied. At the end of each loading cycle deformation is measured externally with the 2 spring-loaded Linear Variable Differential Transducers (LVDT) as shown in Figure 84. Resilient modulus (M_R) is calculated as follows:

$M_R = S_{cyclic} / \varepsilon_r$ ………………………………………………………….. (71)

where, S_{cyclic} = cyclic applied axial stress

ε_r = resilient recovered axial strain= e_r / L where,

e_r = resilient (recovered) axial deformation due to S_{cyclic}; L = original specimen length

Hence, each M_R test results in 15 values of M_R at 15 different combinations of stresses.

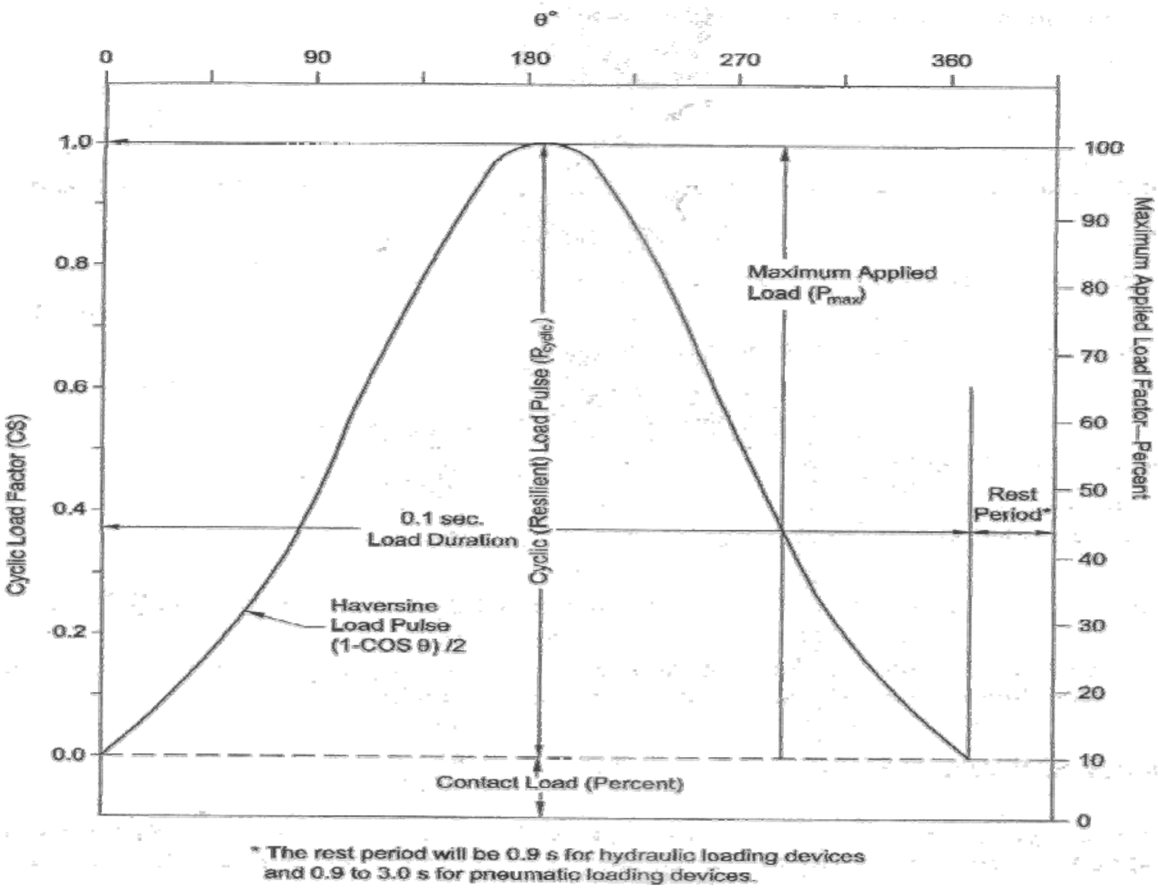


Figure 85. Haversine shaped load pulse used in resilient modulus testing (Figure from AASHTO – T 307)

6.2 Soil Samples Data Collected in New England

Laboratory tests were carried out at the Braun Intertec Corporation, Minneapolis, MN on soil types A-1-b, A-3, A-2-4, A-4, and A-7-6 collected in New England. A-6 soil was not present among the soil samples collected so prediction models for this soil type could not be verified. The laboratory tests include repeated load tests for resilient modulus (M_R), determination of moisture content and density of the soil specimen used for the M_R test, sieve analysis and atterberg limit tests for identifying the soils as per AASHTO soil classification system and proctor tests for determination of optimum moisture content and maximum dry density,.

Soil samples from 3 different sites in Connecticut and 2 different sites in Vermont collected by the Connecticut Department of Transportation and Vermont Agency of Transportation were sent to the Braun Intertec Corporation, MN. Details of the soil collection site and their visual description are presented in Table 19.

Table 19. Soil samples collection site and their visual description

Sample #	Location	Visual Description
CONNECTICUT		
CT-01	Indian Well State Park, Shelton, CT	Sand and Gravel
CT-03	North Branford, Route 80, CT	Glacial till, Reddish Brown
CT-04	North Branford, Route 80, CT	Glacial till, Reddish Brown
CT-12	North Branford, Route 80, CT	Glacial till, Reddish Brown
CT-05	New Milford, Route 7,CT	Silt with Sand, Light Brown
CT-06	New Milford, Route 7,CT	Silt with Sand, Light Brown
CT-13	New Milford, Route 7,CT	Silt with Sand, Light Brown
CT-07	New Milford, Route 7,CT	Sand, Light Brown
CT-08	New Milford, Route 7,CT	Sand, Light Brown
CT-14	New Milford, Route 7,CT	Sand, Light Brown
VERMONT		
VT-01	S. Burlington, VT	Clay, Grey
VT-02	S. Burlington, VT	Clay, Grey
VT-03	S. Burlington, VT	Clay, Grey
VT-04	Hardwick, VT	Lean Clay, Grey/Brown
VT-05	Hardwick, VT	Lean Clay, Grey/Brown
VT-06	Hardwick, VT	Lean Clay, Grey/Brown

6.3 Soil Physical Properties and Soil Classification of the Collected Soil Samples

Each soil sample was tested to obtain data about its physical properties. Sieve tests and hydrometer tests were conducted to obtain the gradation data for the soil samples. Plastic Limit, Liquid Limit and Plasticity Index of the soil samples were determined by Atterberg Limits tests. Proctor test was performed to obtain the optimum moisture content and maximum dry density values required for sample compaction for M_R test. Proctor test plots and Sieve analysis curves has been presented in Appendix G. Moisture content and density of each soil specimen was also measured before the M_R tests. The values of these physical properties have been presented in Table 20 and Table 21 (LL, PI), soil properties notation used are as follows:

Specimen moisture content (MC)
Optimum moisture content (OMC)
Moisture content ratio (MCR=MC/OMC)
Specimen dry density (DD)
Maximum dry density (MAXDD)
Dry density ratio (DDR=DD/MAXDD)
Liquid limit (LL)
Plasticity Index limit (PI)

Uniformity coefficient (CU)	Coefficient of Curvature (CC)
Percent passing 3" sieve (S3)	Percent passing 2" sieve (S2)
Percent passing 1 1/2" sieve (S1_HALF)	Percent passing 1" sieve (S1)
Percent passing 3/4" sieve (S3_4)	Percent passing 1/2" sieve (S1_2)
Percent passing 3/8" sieve (S3_8)	Percent passing #4 sieve (SN4)
Percent passing #10 sieve (SN10)	Percent passing #40 sieve (SN40)
Percent passing #80 sieve (SN80)	Percent passing #200 sieve (SN200)

Percent coarse sand (CSAND, particles of size 2 – 0.42 mm)
Percent fine sand (FSAND, particles of size 0.42 - .074 mm)
Percent silt (SILT, particles of size 0.074 – 0.002 mm)
Percent clay (CLAY, particles of size 0.002 mm)

Based on the sieve analysis and atterberg limits tests results, the AASHTO classification of the soil samples collected are as presented in Table 21.

Table 20. Physical Properties of the tested soil samples

Sample #	MC %	OMC %	MCR	DD kg/cum	MAXDD kg/cum	DDR	CU	CC	S3 %	S2 %	S1_HALF %	S1 %	S3_4 %
CT-01	11.2	11.2	1.00	1841.1	1944.6	0.95	10.09	1.10	100	100	100	98	95
CT-03	10.6	10.3	1.03	1902.8	1992.7	0.95	463.64	0.58	100	94	88	78	73
CT-04	11.0	11.1	0.99	1886.2	1976.7	0.95	212.77	0.98	100	98	95	87	82
CT-12	10.7	10.0	1.07	1898.7	2000.7	0.95	270	0.32	100	93	83	75	71
CT-05	17.7	17.5	1.01	1558.8	1662.7	0.94	-	-	100	100	100	100	100
CT-06	17.4	17.4	1.00	1564.9	1657.9	0.94	-	-	100	100	100	100	100
CT-13	17.5	17.4	1.01	1573.5	1657.9	0.95	-	-	100	100	100	100	100
CT-07	14.2	14.7	0.97	1563.9	1641.9	0.95	2.77	1.20	100	100	100	100	100
CT-08	12.8	12.5	1.02	1567.4	1669.1	0.94	2.57	0.92	100	100	100	100	100
CT-14	14.5	13.8	1.05	1562.7	1654.7	0.94	2.25	0.98	100	100	100	100	100
VT-01	31.2	30.3	1.03	1333.5	1419.2	0.94	-	-	100	100	100	100	100
VT-02	30.4	30.5	1.00	1332.0	1420.8	0.94	-	-	100	100	100	100	100
VT-03	30.8	30.4	1.01	1340.2	1424.0	0.94	-	-	100	100	100	100	100
VT-04	13.8	14.2	0.98	1771.9	1853.3	0.96	-	-	100	100	100	100	100
VT-05	15.9	15.5	1.03	1715.2	1826.1	0.94	-	-	100	100	100	100	100
VT-06	16.5	16.1	1.03	1676.4	1782.9	0.94	-	-	100	100	100	100	100

Table 20. Physical Properties of the tested soil samples *(Cont'd…)*

Sample #	S1_2 %	S3_8 %	SN4 %	SN10 %	SN20 %	SN40 %	SN80 %	SN200 %	CSAND %	FSAND %	SILT %	CLAY %
CT-01	90	86	79	69	54	35	15	5	34.0	30.0	4	1
CT-03	67	65	59	52	46	39	30	23.3	13.0	15.7	18.1	5.2
CT-04	77	74	65	62	54	46	36	26.9	16.0	19.1	20.5	6.4
CT-12	66	64	59	52	45	38	30	22.8	14.0	15.2	17.5	5.3
CT-05	100	100	100	99.8	99.3	98.3	94.9	79.0	1.5	19.3	75.1	3.9
CT-06	100	100	100	99.9	99.6	98.9	96.3	74.5	1.0	24.5	71.5	2.9
CT-13	100	100	99.9	99.8	99.4	98.4	94.8	74.4	1.4	24.0	70.8	3.7
CT-07	100	100	99.8	99.1	96.6	79.3	22.9	3.1	19.8	76.2	2.4	0.7
CT-08	100	100	99.5	98.3	94.3	69.4	17.7	4.0	28.9	65.4	2.9	1.1
CT-14	100	100	99.8	99.1	95.9	75.5	19.4	2.6	23.5	72.9	1.9	0.7
VT-01	100	100	100	99.9	99.7	99.6	99.4	99.0	0.3	0.5	9.6	89.4
VT-02	100	100	100	99.7	99.6	99.4	98.9	98.3	0.4	1.1	10.7	87.6
VT-03	100	100	99.9	99.8	99.7	99.6	99.2	98.8	0.2	0.8	11.4	87.4
VT-04	100	100	99.7	98.9	97.2	94.5	89.8	81.9	4.5	12.6	61.3	20.6
VT-05	100	100	99.8	98.6	96.5	93.6	88.1	77.6	5.0	16.0	58.9	18.7
VT-06	100	100	100	99.9	98.9	96.8	92.9	84.3	3.0	12.5	64.5	19.8

Table 21. AASHTO and USCS Soil Classification of the soil samples

Sample #	Sieve Analysis (% Passing)			LL	PI	AASHTO Class.	USCS Classification (Description)
	SN10	SN40	SN200				
CT-01	69	35	5	22	NP	A-1-b	Coarse Grained; SP-SM (Poorly graded sand with silt & gravel)
CT-03	52	39	23.3	29	6	A-1-b	Coarse Grained; GM (Silty gravel with sand)
CT-04	62	46	26.9	28	6	A-2-4	Coarse Grained; SC-SM (Silty clayey sand with gravel)
CT-12	52	38	22.8	27	6	A-1-b	Coarse Grained; GC-GM(Silty clayey gravel with sand)
CT-05	99.77	98.3	78.99	25	NP	A-4	Fine Grained; ML (Silt with sand)
CT-06	99.93	98.91	74.45	24	NP	A-4	Fine Grained; ML (Silt with sand)
CT-13	99.79	98.42	74.43	25	NP	A-4	Fine Grained; ML (Silt with sand)
CT-07	99.07	79.28	3.12	18	NP	A-3	Coarse Grained; SP (Poorly graded sand)
CT-08	98.32	69.39	4	18	NP	A-3	Coarse Grained; SP (Poorly graded sand)
CT-14	99.06	75.51	2.59	17	NP	A-3	Coarse Grained; SP (Poorly graded sand)
VT-01	99.85	99.59	99.04	80	51	A-7-6	Fine Grained; CH (Fat Clay)
VT-02	99.74	99.36	98.3	76	47	A-7-6	Fine Grained; CH (Fat Clay)
VT-03	99.78	99.57	98.79	79	49	A-7-5	Fine Grained; CH (Fat Clay)
VT-04	98.94	94.47	81.89	28	8	A-4	Fine Grained; CL (Lean clay with sand)
VT-05	98.63	93.61	77.63	26	8	A-4	Fine Grained; CL (Lean clay with sand)
VT-06	99.86	96.81	84.27	27	8	A-4	Fine Grained; CL (Lean clay with sand)

6.4 Laboratory Resilient Modulus Test Results

Resilient modulus (M_R) values for the soil samples were determined by conducting repeated load triaxial test according to AASHTO Standard - T 307. All soil samples were compacted at optimum moisture content for M_R testing as obtained from proctor tests. Figure 86 shows the M_R test in progress at the Braun Intertec Corporation, MN laboratories. The results of M_R tests have been presented in Tables 22 to 26 along with the calculated values for bulk stress and octahedral shear stress. Plots for laboratory M_R vs. deviator stress at 3 levels of confining pressure for each of the 16 soil samples have been presented in Figure 87 to 102.

Figure 86. Resilient Modulus test in Progress

Table 22. Laboratory M_R test results for A-1-b (Coarse Grained) soils

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahderal Shear Stress, τ_{oct} kPa	Lab M_R MPa
CT-01	41.4	12.4	136.543	5.844	90
CT-01	41.3	24.9	148.9107	11.73	95
CT-01	41.4	37.3	161.3396	17.57	96
CT-01	41.4	49.6	173.7291	23.397	97
CT-01	41.3	62.0	185.9857	29.209	98
CT-01	27.6	12.2	94.95913	5.76	66
CT-01	27.6	24.5	107.3068	11.536	67
CT-01	27.6	37.1	119.7979	17.467	71
CT-01	27.6	49.6	132.2365	23.37	76
CT-01	27.6	61.9	144.558	29.165	78
CT-01	13.8	12.2	53.54541	5.743	45
CT-01	13.8	24.4	65.77769	11.487	47
CT-01	13.8	36.8	78.25656	17.369	51
CT-03	41.4	12.6	136.7239	5.936	112
CT-03	41.4	25.3	149.3539	11.919	111
CT-03	41.4	37.7	161.7791	17.777	103
CT-03	41.3	49.9	173.9062	23.503	98
CT-03	41.4	62.4	186.4499	29.406	95
CT-03	27.6	12.6	95.37337	5.95	96
CT-03	27.6	25.2	107.8967	11.857	93
CT-03	27.6	37.7	120.3987	17.755	89
CT-03	27.6	49.9	132.5941	23.508	86
CT-03	27.6	62.3	145.0699	29.392	85
CT-03	13.8	12.6	53.91231	5.923	68
CT-03	13.8	25.0	66.36555	11.806	67
CT-03	13.8	37.3	78.65348	17.59	67
CT-03	13.8	49.7	91.0308	23.434	68
CT-03	13.8	62.2	103.6077	29.309	69
CT-12	41.4	12.6	136.7673	5.929	104
CT-12	41.4	25.1	149.2869	11.853	99
CT-12	41.4	37.6	161.6882	17.712	91
CT-12	41.4	49.8	173.8793	23.479	86
CT-12	41.3	62.2	186.2572	29.329	84
CT-12	27.6	12.6	95.25718	5.925	90
CT-12	27.6	25.0	107.6961	11.794	83
CT-12	27.6	37.3	120.0017	17.593	77
CT-12	27.6	49.7	132.3444	23.413	74
CT-12	27.6	62.2	145.0164	29.334	74
CT-12	13.8	12.5	53.75588	5.888	70
CT-12	13.8	24.9	66.23222	11.728	64
CT-12	13.8	37.1	78.47615	17.503	61
CT-12	13.8	49.5	90.89508	23.358	60
CT-12	13.8	62.0	103.3961	29.249	61

Table 23. Laboratory M_R test results for A-3 (Coarse Grained) soils

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahedral Shear Stress, τ_{oct} kPa	Lab M_R MPa
CT-07	41.3	12.6	136.5905	5.947	64
CT-07	41.4	25.3	149.4866	11.919	66
CT-07	41.4	37.7	161.9598	17.783	67
CT-07	41.4	50.6	174.752	23.83	71
CT-07	41.4	62.7	186.8535	29.556	73
CT-07	27.5	12.2	94.69771	5.756	51
CT-07	27.5	25.3	107.8166	11.905	51
CT-07	27.6	37.5	120.3219	17.659	54
CT-07	27.6	50.1	132.8616	23.63	58
CT-07	27.6	62.5	145.2339	29.439	60
CT-07	13.8	12.4	53.91801	5.851	35
CT-07	13.8	24.8	66.22381	11.693	36
CT-07	13.8	37.4	78.80285	17.631	40
CT-07	13.8	49.6	91.03409	23.38	41
CT-07	13.8	61.4	102.7483	28.951	37
CT-08	41.4	12.6	136.6537	5.919	67
CT-08	41.4	25.2	149.3595	11.865	70
CT-08	41.4	37.8	161.914	17.802	71
CT-08	41.4	50.2	174.2608	23.66	72
CT-08	41.4	62.7	186.8934	29.579	74
CT-08	27.6	12.6	95.30595	5.924	54
CT-08	27.6	25.2	107.9834	11.886	54
CT-08	27.6	37.8	120.6766	17.825	56
CT-08	27.6	50.1	132.969	23.634	59
CT-08	27.6	62.5	145.2926	29.458	60
CT-08	13.8	12.4	53.70986	5.824	36
CT-08	13.8	24.8	66.16688	11.685	37
CT-08	13.8	37.4	78.8666	17.63	40
CT-08	13.8	49.5	90.9581	23.325	39
CT-08	13.8	60.9	102.2483	28.704	29
CT-14	41.4	12.6	136.7031	5.934	63
CT-14	41.4	25.3	149.4199	11.905	66
CT-14	41.4	37.6	161.786	17.739	67
CT-14	41.4	50.1	174.2319	23.612	69
CT-14	41.4	62.6	186.7343	29.509	71
CT-14	27.6	12.5	95.32549	5.911	49
CT-14	27.6	25.1	107.8543	11.822	49
CT-14	27.6	37.7	120.4716	17.782	52
CT-14	27.6	50.0	132.7295	23.568	55
CT-14	27.6	62.4	145.1931	29.413	57
CT-14	14.0	12.3	54.18592	5.808	32
CT-14	13.8	24.7	66.09768	11.645	33
CT-14	13.8	37.3	78.85482	17.593	36
CT-14	13.8	49.7	91.10129	23.422	38
CT-14	13.8	61.8	103.2447	29.111	38

Table 24. Laboratory M_R test results for A-2-4 (Coarse Grained) soils

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahderal Shear Stress, τ_{oct} kPa	Lab M_R MPa
CT-04	41.3	12.6	136.5689	5.919	92
CT-04	41.3	25.0	149.0083	11.772	86
CT-04	41.3	37.2	161.2724	17.553	77
CT-04	41.4	49.6	173.6883	23.383	74
CT-04	41.4	62.1	186.1239	29.256	72
CT-04	27.6	12.5	95.25759	5.904	79
CT-04	27.6	24.8	107.5474	11.71	70
CT-04	27.6	37.2	119.8765	17.518	64
CT-04	27.6	49.6	132.2627	23.358	62
CT-04	27.6	62.0	144.6556	29.215	62
CT-04	13.8	12.3	53.63836	5.819	57
CT-04	13.8	24.4	65.77119	11.524	51
CT-04	13.8	36.8	78.11476	17.338	48
CT-04	13.8	49.2	90.58614	23.208	48
CT-04	13.8	61.7	103.1086	29.107	50

Table 25. Laboratory M_R test results for A-4 (Fine Grained) soils

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahderal Shear Stress, τ_{oct} kPa	Lab M_R MPa
CT-05	41.4	12.6	136.67935	5.937	68
CT-05	41.4	25.3	149.36222	11.912	63
CT-05	41.4	37.7	161.78323	17.751	60
CT-05	41.4	50.1	174.2208	23.623	59
CT-05	41.4	62.6	186.7269	29.532	59
CT-05	27.6	12.5	95.343661	5.914	58
CT-05	27.6	24.8	107.61989	11.707	50
CT-05	27.6	37.3	120.02447	17.563	47
CT-05	27.6	50.0	132.76306	23.562	46
CT-05	27.6	62.8	145.56705	29.613	47
CT-05	13.8	12.3	53.745617	5.805	38
CT-05	13.8	24.5	65.938742	11.541	33
CT-05	13.8	36.9	78.34112	17.391	32
CT-05	13.8	49.5	90.892613	23.325	33
CT-05	13.8	62.1	103.4879	29.286	36
CT-06	41.4	12.6	136.62637	5.924	69
CT-06	41.3	25.2	149.25254	11.881	63
CT-06	41.4	37.6	161.6839	17.712	60
CT-06	41.4	49.9	174.00056	23.532	59
CT-06	41.4	62.5	186.52138	29.446	59
CT-06	27.6	12.5	95.300899	5.909	59
CT-06	27.6	24.9	107.61899	11.719	52
CT-06	27.6	37.4	120.15131	17.623	48
CT-06	27.6	50.0	132.75111	23.561	48
CT-06	27.6	62.5	145.20844	29.441	49
CT-06	13.8	12.3	53.610368	5.787	40
CT-06	13.8	24.5	65.808666	11.547	35
CT-06	13.8	37.0	78.265212	17.434	34
CT-06	13.8	49.5	90.88181	23.347	36
CT-06	13.8	62.3	103.6967	29.39	38
CT-13	41.4	12.5	136.57578	5.895	56
CT-13	41.4	25.2	149.29333	11.897	53
CT-13	41.4	37.6	161.80361	17.745	52
CT-13	41.4	49.9	174.07	23.537	53
CT-13	41.4	62.5	186.5935	29.449	55
CT-13	27.6	12.4	95.119469	5.846	47
CT-13	27.6	24.6	107.25223	11.577	42
CT-13	27.6	37.2	119.89295	17.538	40
CT-13	27.6	49.7	132.46311	23.425	41
CT-13	27.6	62.4	145.13708	29.405	44
CT-13	13.8	12.3	53.582594	5.775	33
CT-13	13.8	24.5	65.79649	11.531	29
CT-13	13.8	36.9	78.169296	17.376	29
CT-13	13.8	49.5	90.882563	23.339	31
CT-13	13.8	62.3	103.71662	29.372	34

Table 25. Laboratory M_R test results for A-4 (Fine Grained) soils *(Cont'd…)*

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahderal Shear Stress, τ_{oct} kPa	Lab M_R MPa
VT-04	41.4	12.6	136.6791	5.95	94
VT-04	41.4	25.3	149.32052	11.908	90
VT-04	41.3	37.8	161.8577	17.825	83
VT-04	41.4	50.1	174.19846	23.615	78
VT-04	41.4	62.5	186.54664	29.447	76
VT-04	27.6	12.6	95.349671	5.928	88
VT-04	27.6	25.2	108.01081	11.902	82
VT-04	27.6	37.8	120.52665	17.811	75
VT-04	27.6	50.0	132.73459	23.568	71
VT-04	27.6	62.3	145.04165	29.371	69
VT-04	13.8	12.6	53.946417	5.937	72
VT-04	13.8	25.1	66.497167	11.854	67
VT-04	13.8	37.5	78.863724	17.675	63
VT-04	13.8	49.8	91.193384	23.483	60
VT-04	13.8	62.4	103.72694	29.399	59
VT-05	41.4	12.6	136.67845	5.929	79
VT-05	41.3	25.2	149.16981	11.903	74
VT-05	41.4	37.5	161.71069	17.66	66
VT-05	41.4	49.8	173.98635	23.464	62
VT-05	41.4	62.1	186.24675	29.266	59
VT-05	27.6	12.6	95.52189	5.943	71
VT-05	27.6	25.1	107.96925	11.841	64
VT-05	27.6	37.3	120.00006	17.565	58
VT-05	27.6	49.6	132.36304	23.367	54
VT-05	27.6	62.0	144.7532	29.233	53
VT-05	13.8	12.5	53.839035	5.871	56
VT-05	13.8	24.8	66.154948	11.681	51
VT-05	13.8	36.9	78.278307	17.4	47
VT-05	13.8	49.1	90.510912	23.169	45
VT-05	13.8	61.6	102.92035	29.032	45
VT-06	41.4	12.5	136.68828	5.914	81
VT-06	41.4	25.1	149.39311	11.854	75
VT-06	41.4	37.4	161.50152	17.611	67
VT-06	41.4	49.7	173.79832	23.425	62
VT-06	41.3	62.0	186.04094	29.247	60
VT-06	27.6	12.5	95.243397	5.909	73
VT-06	27.6	25.0	107.92507	11.794	65
VT-06	27.6	37.3	120.04764	17.563	58
VT-06	27.5	49.5	132.16895	23.345	54
VT-06	27.5	62.0	144.61745	29.223	52
VT-06	13.7	12.5	53.735835	5.894	57
VT-06	13.8	24.8	66.15318	11.682	51
VT-06	13.8	37.0	78.326238	17.439	47
VT-06	13.8	49.1	90.54253	23.165	45
VT-06	13.8	61.6	103.0546	29.045	44

Table 26. Laboratory M_R test results for A-7-6 (Fine Grained) soils

Sample #	Confining Pressure, σ_3 kPa	Deviator/Applied Cyclic Stress, σ_d kPa	Bulk Stress, θ kPa	Octahderal Shear Stress, τ_{oct} kPa	Lab M_R MPa
VT-01	41.3	12.5	136.5551	5.897	70
VT-01	41.4	25.0	149.0687	11.768	69
VT-01	41.4	37.3	161.4119	17.594	65
VT-01	41.4	49.5	173.5723	23.337	61
VT-01	41.3	61.8	185.8015	29.111	58
VT-01	27.6	12.5	95.1744	5.876	65
VT-01	27.6	24.9	107.6087	11.747	64
VT-01	27.6	37.2	119.8995	17.544	61
VT-01	27.6	49.4	132.0691	23.291	58
VT-01	27.6	61.8	144.5699	29.112	56
VT-01	13.8	12.4	53.7749	5.841	50
VT-01	13.8	24.7	66.0944	11.662	53
VT-01	13.8	37.1	78.4231	17.489	54
VT-01	13.8	49.3	90.6679	23.252	53
VT-01	13.8	61.6	102.9336	29.05	52
VT-02	41.4	12.5	136.5949	5.898	61
VT-02	41.4	25.0	149.0234	11.77	59
VT-02	41.3	37.1	161.1261	17.489	55
VT-02	41.4	49.3	173.3716	23.227	52
VT-02	41.4	61.4	185.4293	28.923	48
VT-02	27.5	12.5	95.1050	5.883	57
VT-02	27.6	24.9	107.7341	11.747	56
VT-02	27.6	37.1	119.8738	17.473	54
VT-02	27.6	49.1	131.8940	23.163	51
VT-02	27.6	61.4	144.2530	28.961	49
VT-02	13.8	12.3	53.8014	5.815	44
VT-02	13.8	24.6	66.0137	11.594	45
VT-02	13.8	36.8	78.2077	17.36	44
VT-02	13.8	48.9	90.3551	23.052	44
VT-02	13.8	61.2	102.5254	28.834	43
VT-03	41.4	12.6	136.6212	5.917	66
VT-03	41.3	24.9	148.9180	11.728	64
VT-03	41.3	37.1	161.1451	17.504	61
VT-03	41.3	49.3	173.3510	23.253	57
VT-03	41.3	61.6	185.6909	29.058	55
VT-03	27.6	12.5	95.2237	5.878	61
VT-03	27.5	24.9	107.5035	11.721	60
VT-03	27.6	37.1	119.8887	17.494	57
VT-03	27.6	49.3	132.2173	23.241	54
VT-03	27.6	61.6	144.3945	29.037	52
VT-03	13.8	12.4	53.8377	5.865	50
VT-03	13.8	24.7	66.0289	11.64	51
VT-03	13.8	36.9	78.3263	17.414	50
VT-03	13.8	49.1	90.4940	23.164	49
VT-03	13.8	61.4	102.7167	28.932	48

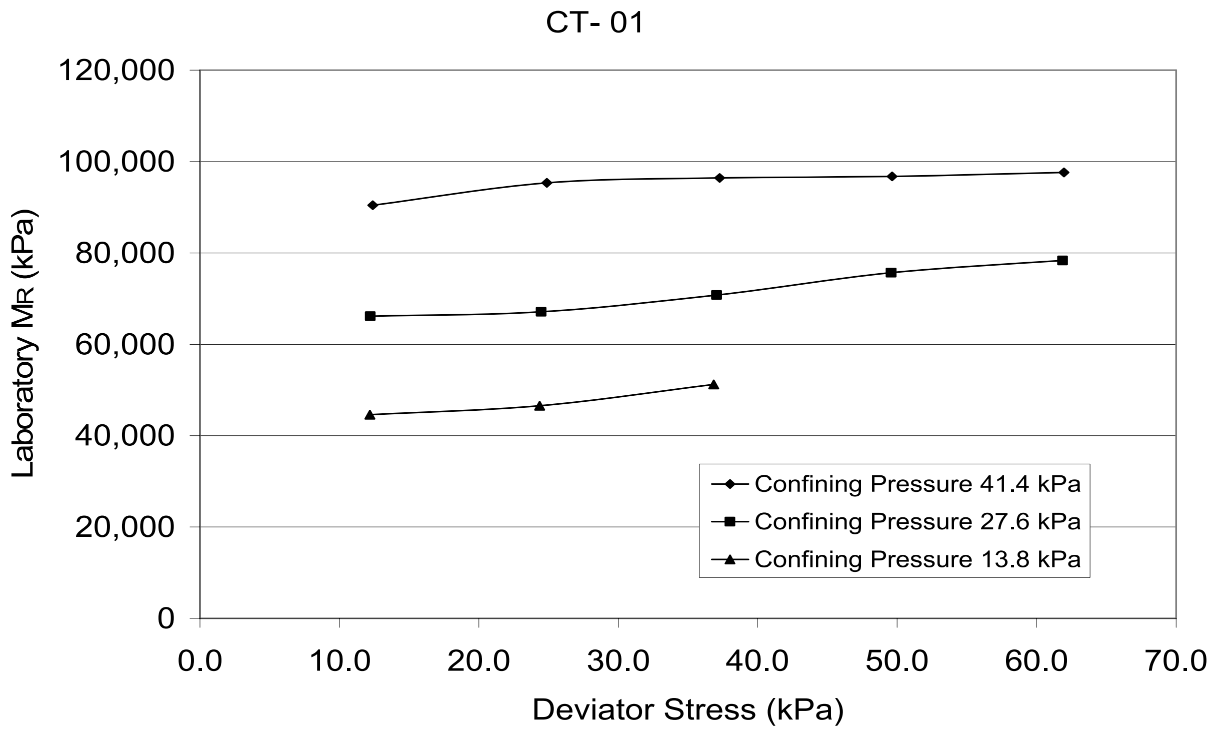


Figure 87. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-01

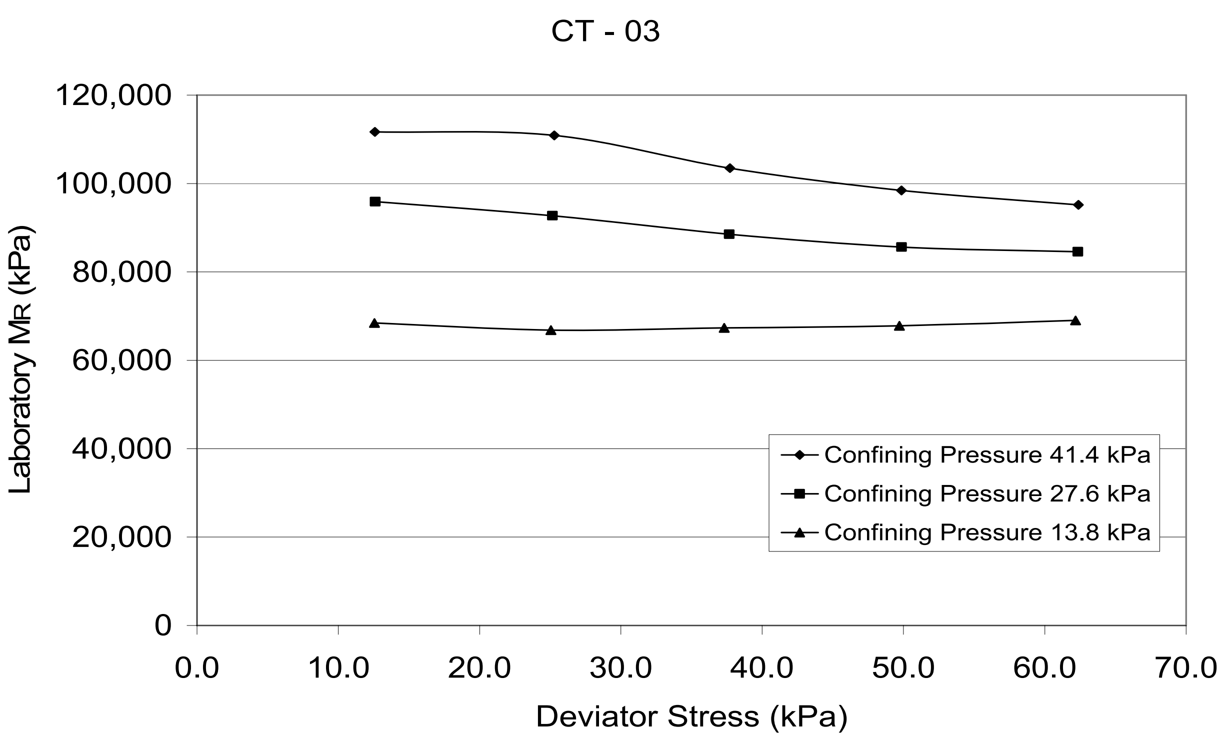


Figure 88. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-03

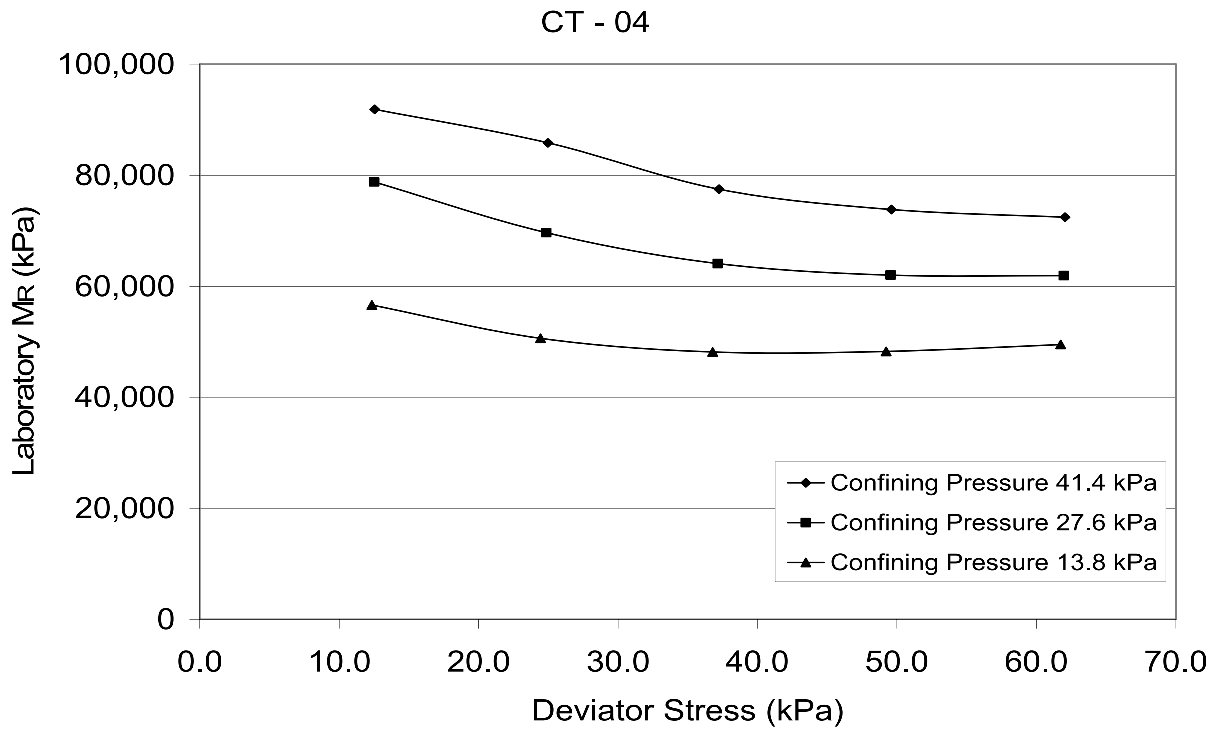


Figure 89. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-04

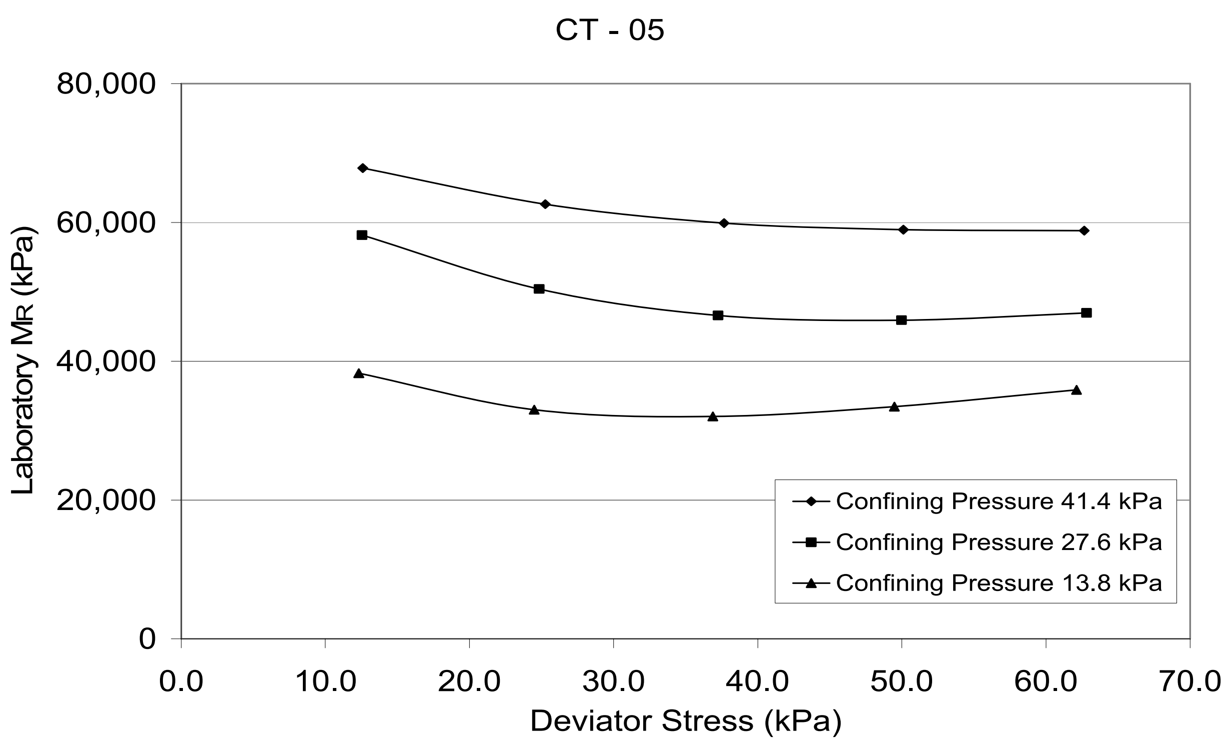


Figure 90. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-05

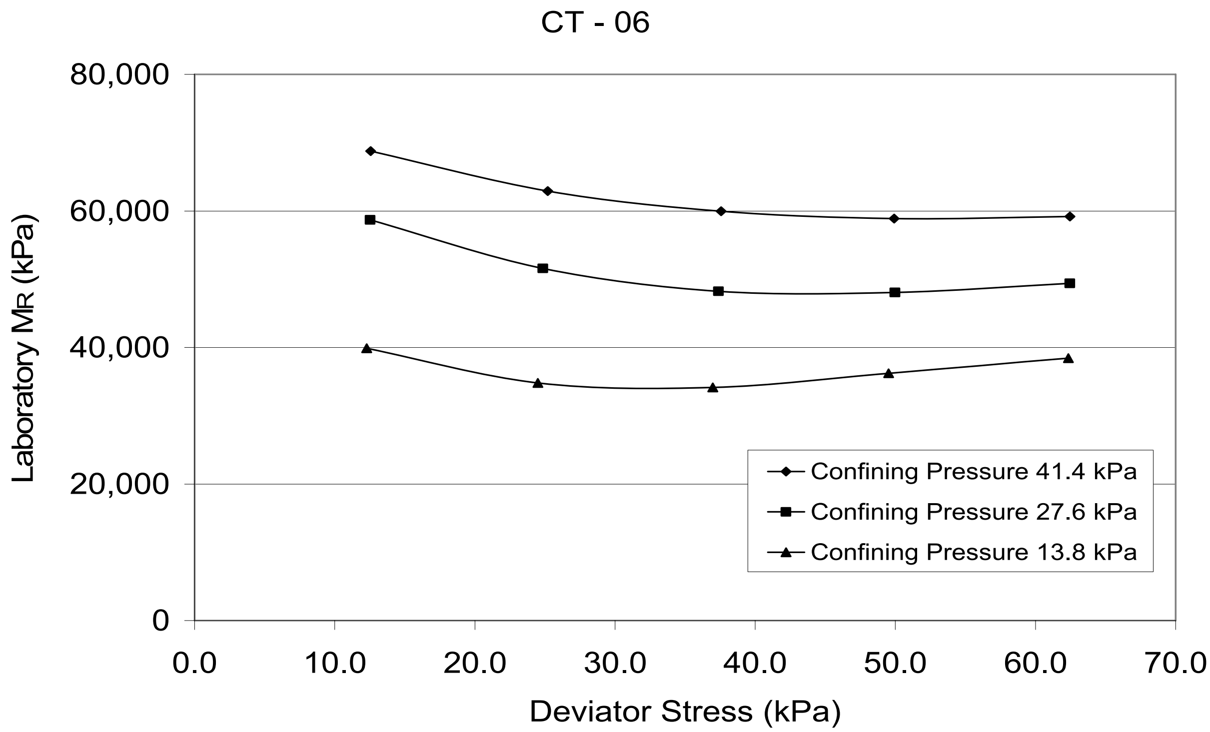


Figure 91. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-06

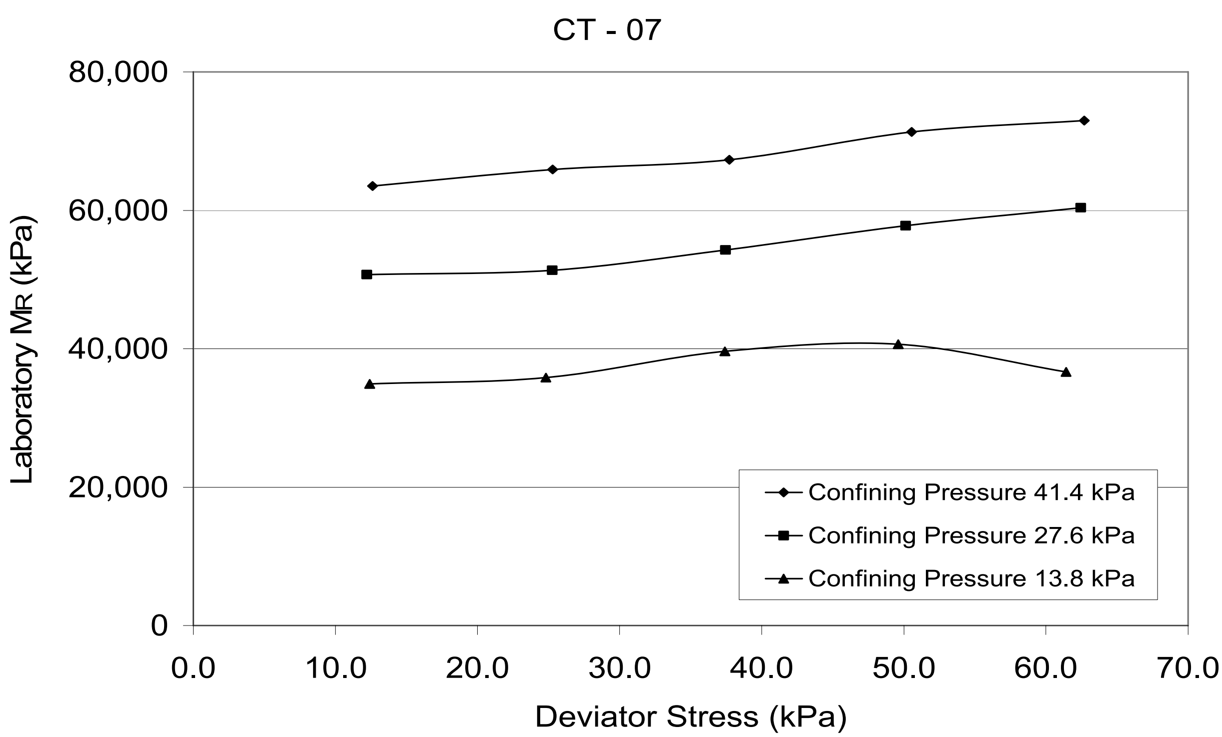


Figure 92. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-07

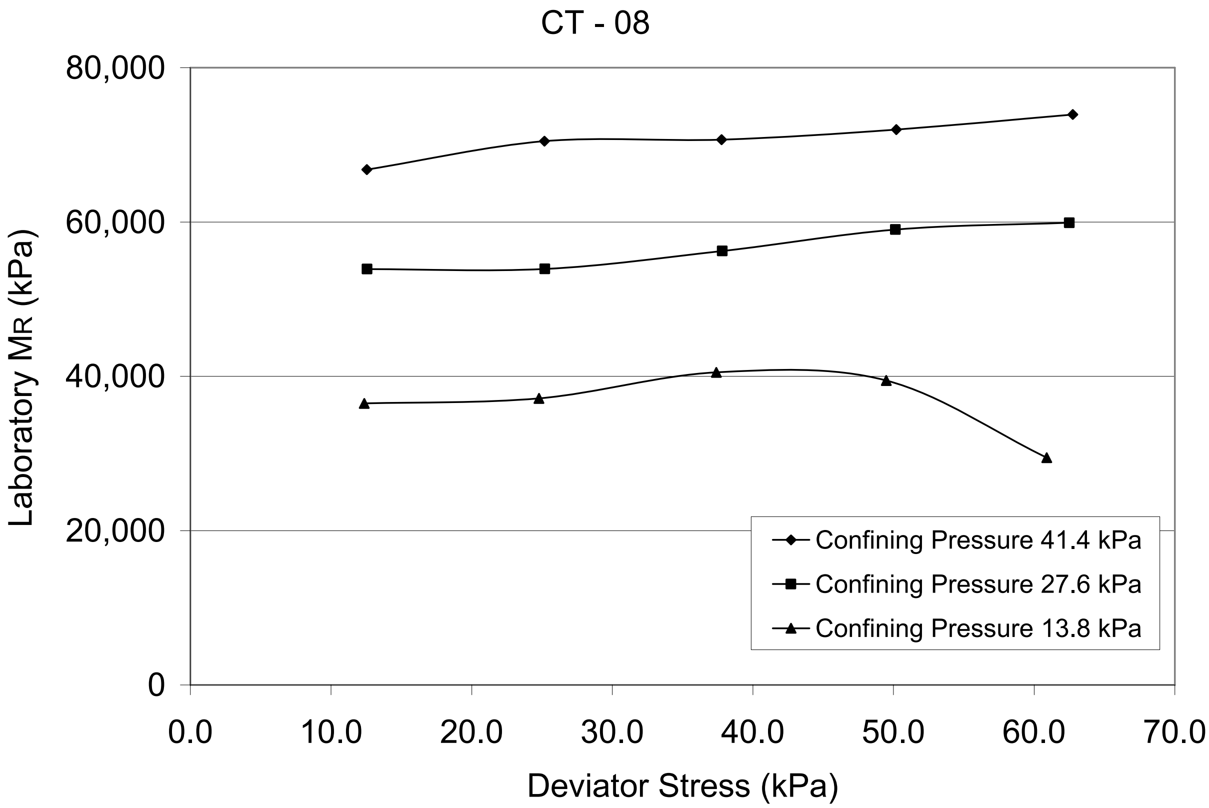


Figure 93. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-08

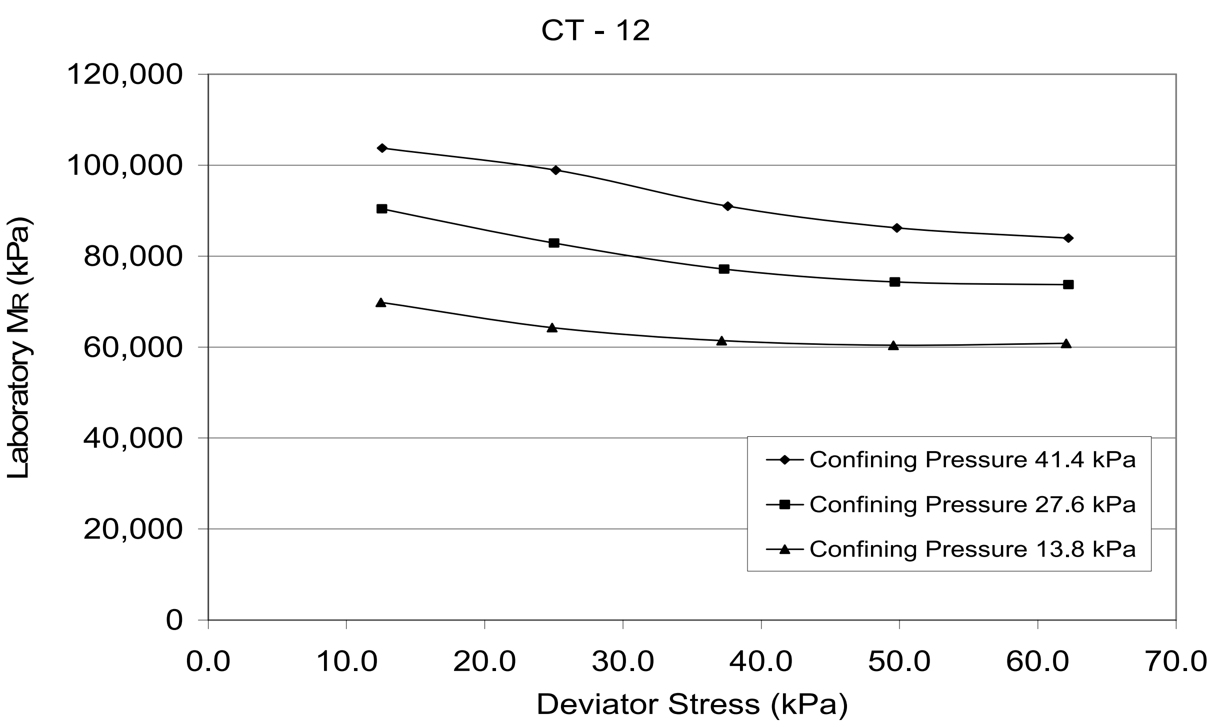


Figure 94. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-12

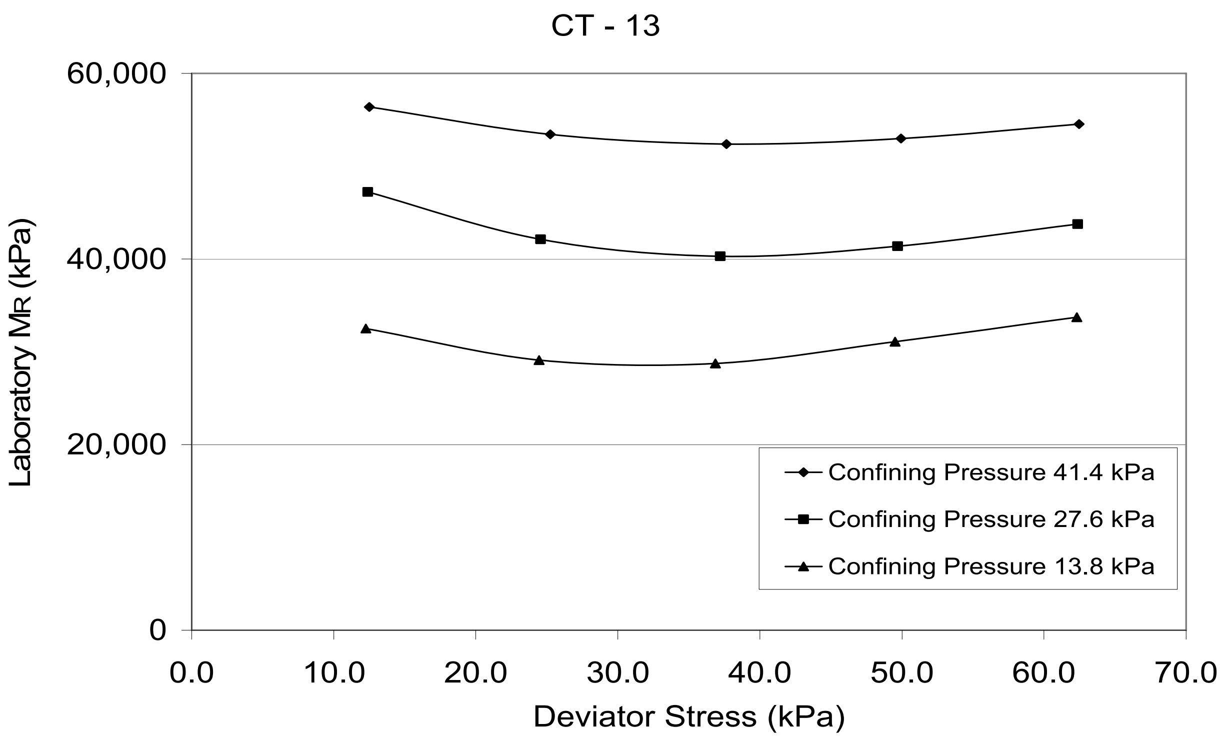


Figure 95. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-13

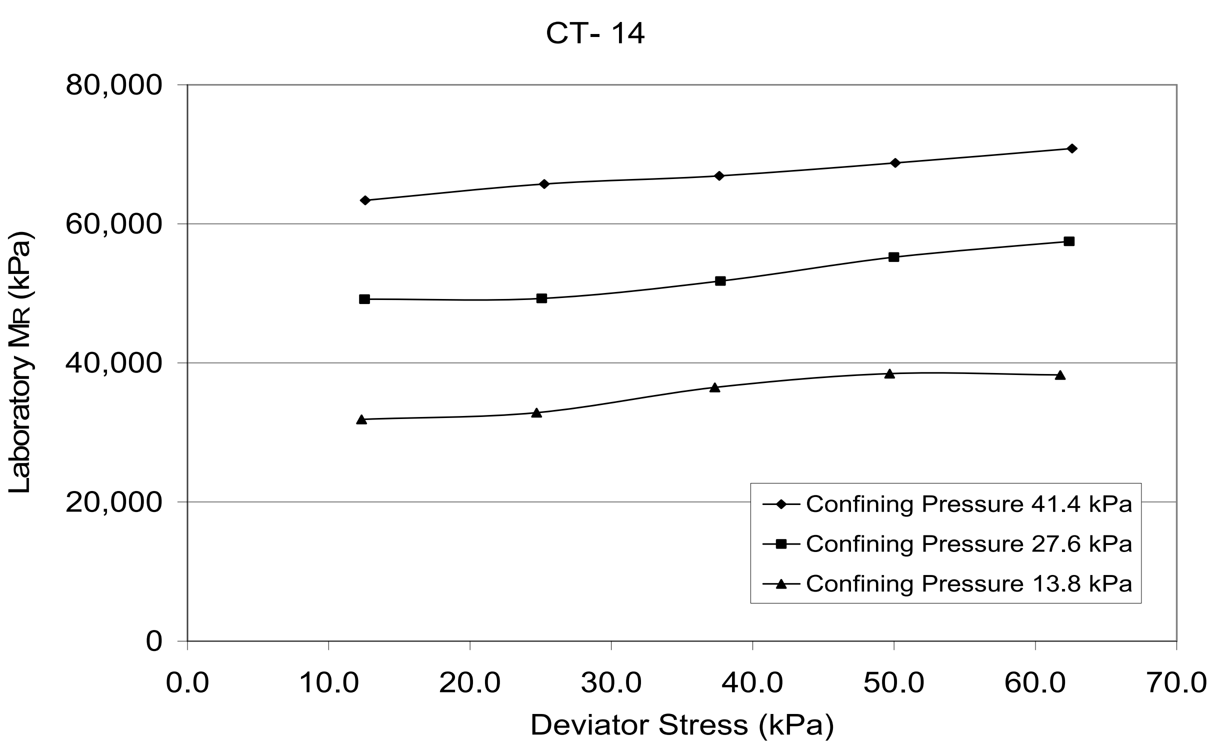


Figure 96. Laboratory Resilient Modulus (M_R) vs. Deviator stress for CT-14

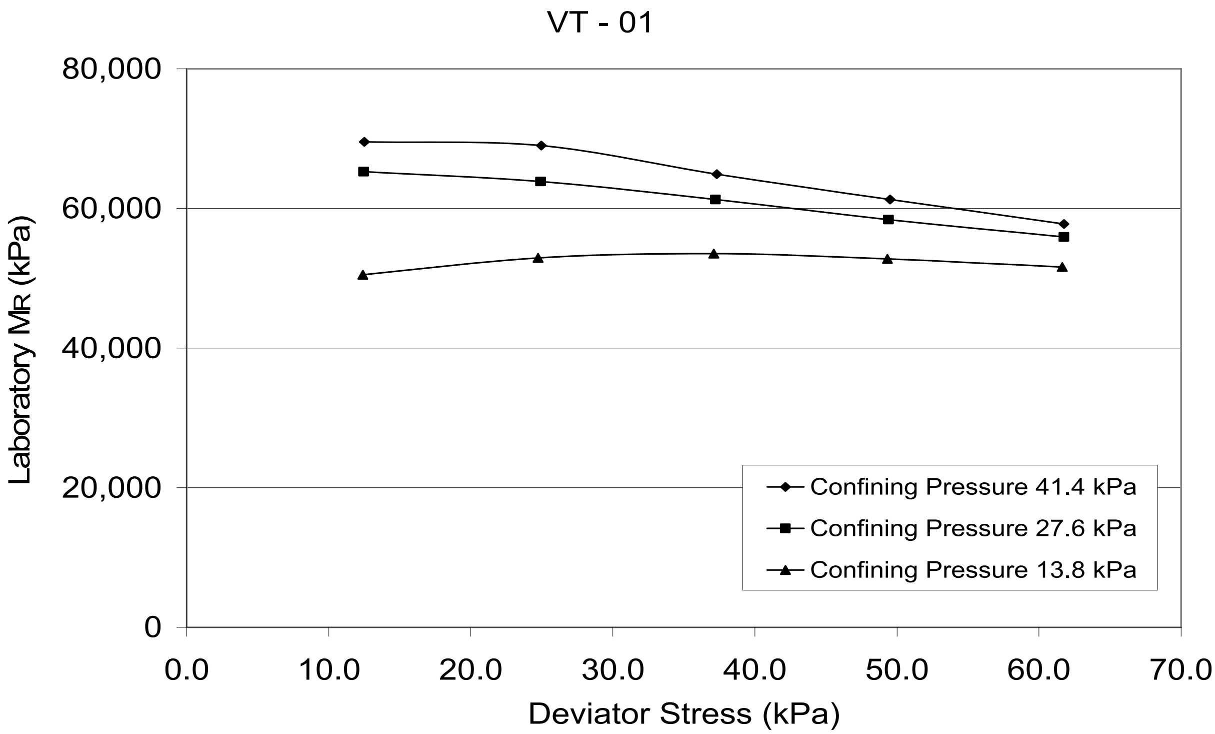


Figure 97. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-01

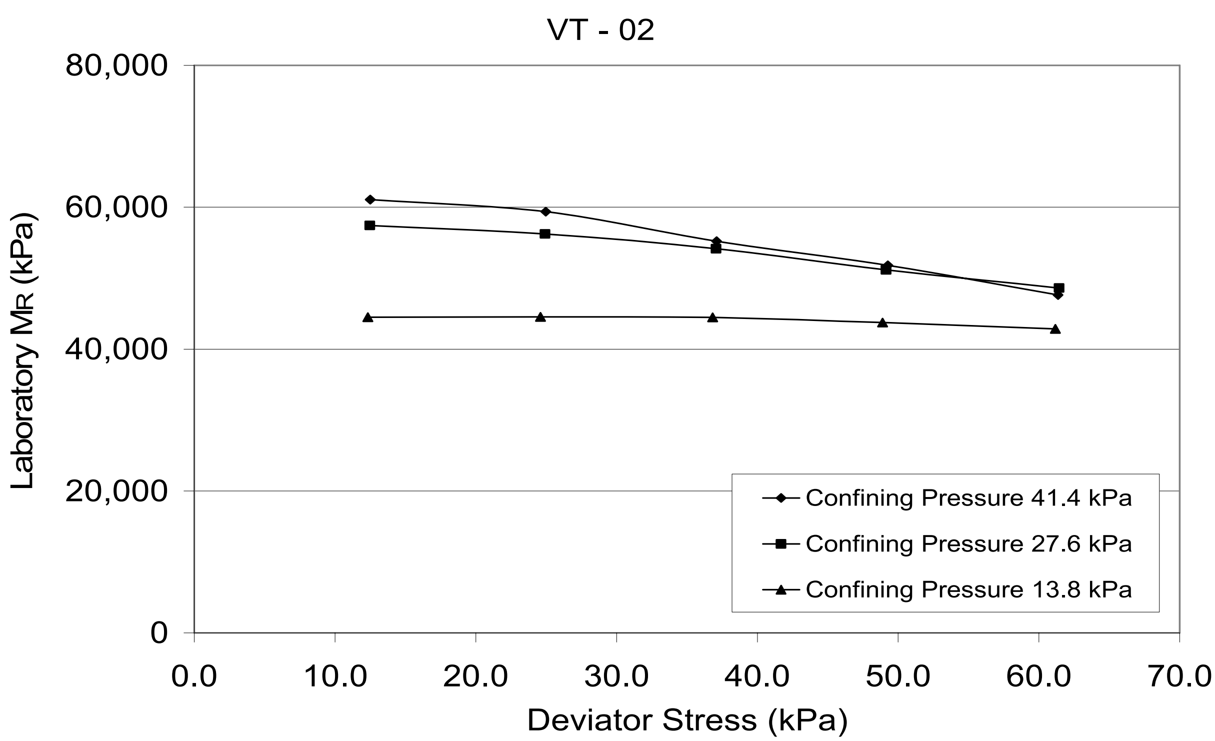


Figure 98. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-02

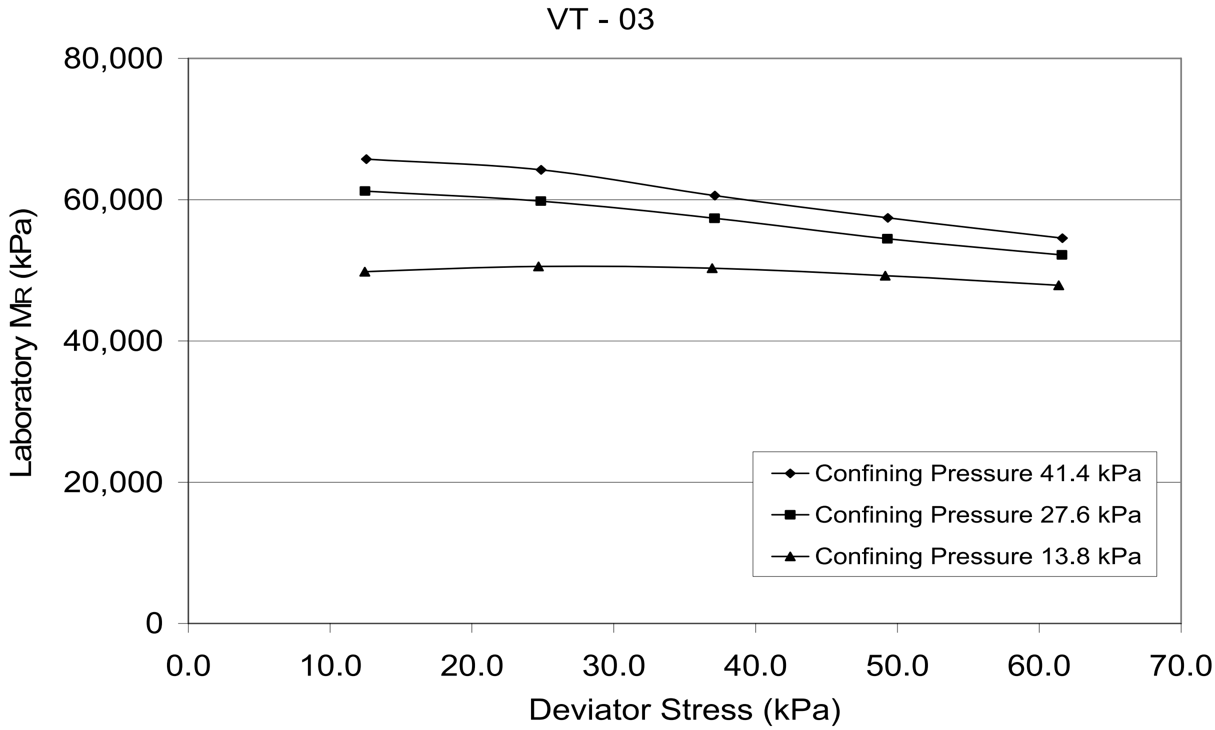


Figure 99. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-03

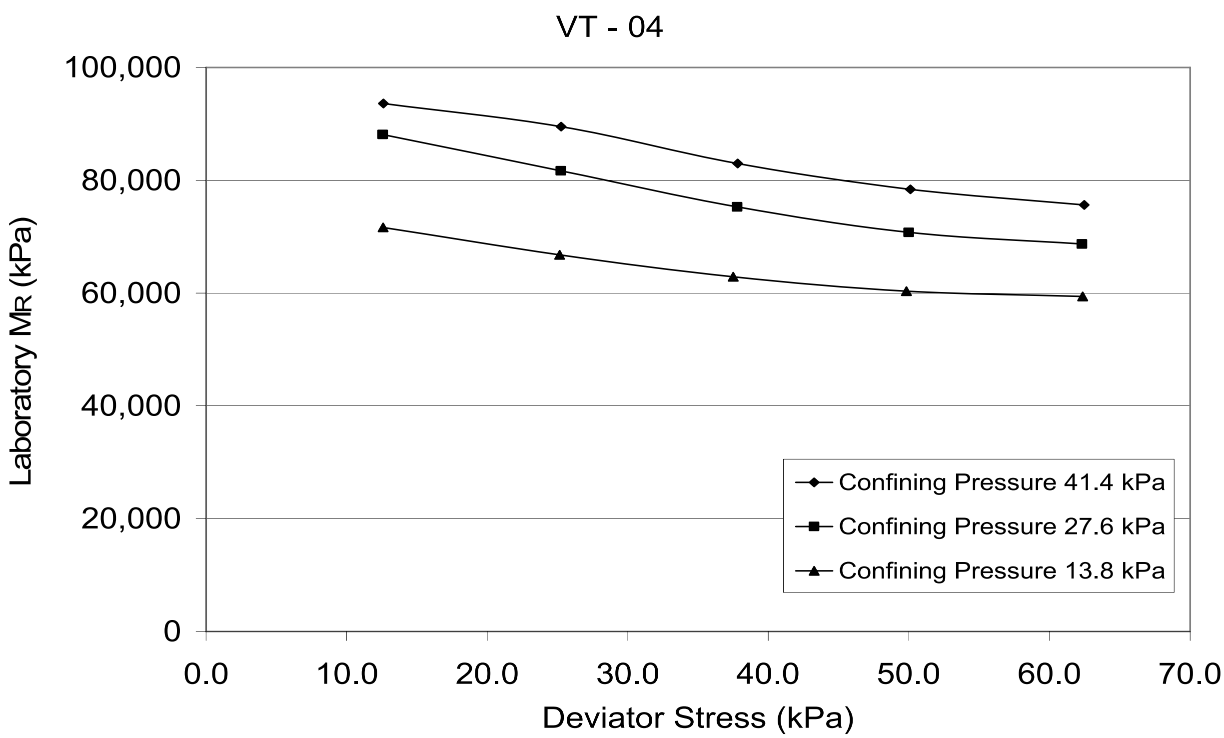


Figure 100. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-04

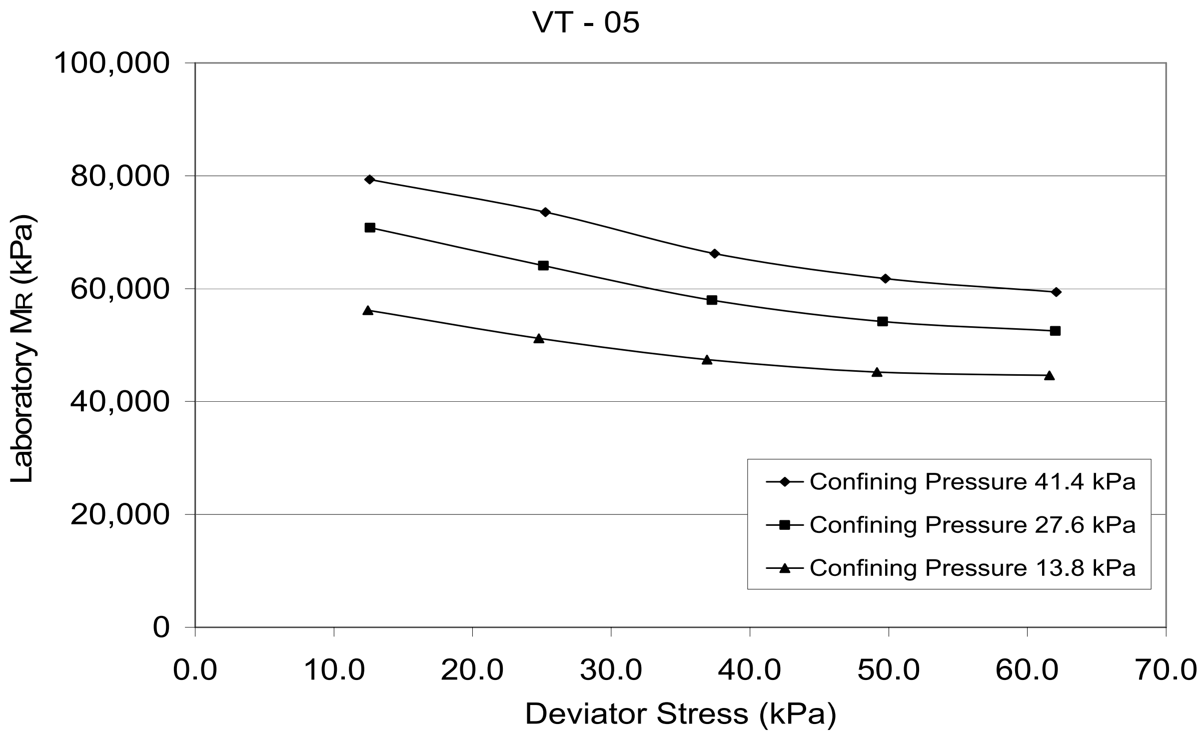


Figure 101. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-05

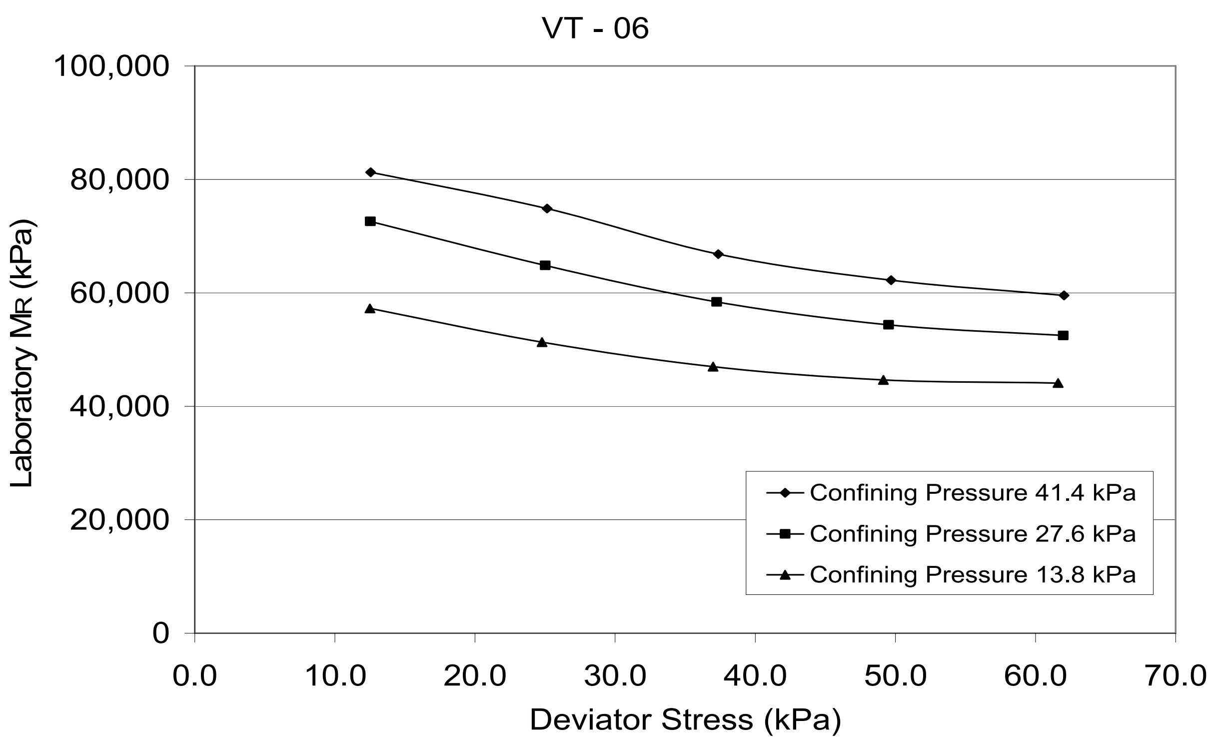


Figure 102. Laboratory Resilient Modulus (M_R) vs. Deviator stress for VT-06

6.5 Verification of Prediction Models Developed for AASHTO Soil Types

In order to verify the prediction models developed in Section 4.3 for the different AASHTO soil types, the values of the soil properties mentioned in the Table 20 were substituted in the corresponding k coefficients equations for each soil type. For each soil sample, k coefficients were determined for 2 set of prediction models (see Section 4.3.3), the first set of models had been developed using all the reconstituted samples and the second set of models had been developed using only those soil samples that were compacted at optimum moisture content which will be referred as MODEL1 and MODEL2 respectively hereafter.

The value of k coefficients obtained from the MODEL1 and MODEL2 for each soil specimen has been presented in Table 27. The values of k coefficients calculated by regression of laboratory M_R values and corresponding stresses using the generalized constitutive model as described in Section 4.3.2 has also been presented in Table 27.

Table 27. Comparison of values k coefficients obtained from regression of each sample and those obtained from the prediction models developed for different AASHTO soil types

Sample #	k coefficients from regression of lab test values			k coefficients evaluated from the prediction models					
				MODEL1*			MODEL2**		
	log k1	k2	k3	log k1	k2	k3	log k1	k2	k3
CT-01	-0.29497	0.82099	-0.11852	-0.16032	0.68906	-0.28038	-0.25161	0.72315	-0.19518
CT-03	-0.28467	0.57236	-0.22403	-0.22894	0.54259	-0.15274	-1.61057	1.31005	-0.33468
CT-12	-0.35937	0.50461	-0.26561	-0.22943	0.44594	-0.1214	-2.1829	1.47774	-0.32714
CT-04	-0.48107	0.61563	-0.31157	-0.60032	0.43058	-0.41346	-0.7757	1.15788	-0.51261
CT-05	-0.6323	0.78118	-0.3186	-0.71994	0.60058	-0.36046	-0.5787	0.45017	-0.30857
CT-06	-0.58682	0.70951	-0.28494	-0.72392	0.61151	-0.3555	-0.56706	0.47583	-0.30164
CT-13	-0.61851	0.74289	-0.23706	-0.72242	0.61551	-0.36015	-0.58046	0.47006	-0.31023
CT-07	-0.43988	0.78383	-0.13487	-0.4652	0.67678	-0.15122	-0.37173	0.67091	-0.15118
CT-08	-0.50591	0.85509	-0.21813	-0.41169	0.62246	-0.15101	-0.32249	0.72017	-0.16151
CT-14	-0.46548	0.8488	-0.14186	-0.43579	0.6458	-0.1455	-0.34911	0.72466	-0.15802
VT-01	-0.36846	0.2883	-0.14468	-0.90371	-0.26108	-0.43303	-0.93935	-0.24357	-0.57419
VT-02	-0.46293	0.30817	-0.1767	-0.84032	-0.19491	-0.40655	-0.88908	-0.22747	-0.54705
VT-03	-0.40204	0.26889	-0.15416	-0.88128	-0.24734	-0.4328	-0.89928	-0.22257	-0.55156
VT-04	-0.34964	0.3558	-0.24126	-0.39967	0.34242	-0.32312	-0.35339	0.3688	-0.2966
VT-05	-0.51023	0.43552	-0.30142	-0.61611	0.41975	-0.40437	-0.62021	0.40431	-0.41173
VT-06	-0.52643	0.45383	-0.32336	-0.57854	0.39203	-0.39273	-0.57341	0.3673	-0.38268

*MODEL1 – Models developed using all the reconstituted samples

**MODEL2 - Models developed using only those soil samples that were compacted at optimum moisture content

After evaluating the value of the k coefficients from the prediction models for each soil sample, the value of k coefficients were substituted in the generalized constitutive model equation, $\log M_R = \log(k_1 P_a) + k_2 \log\left(\frac{\theta}{P_a}\right) + k_3 \log\left(\frac{\tau_{oct}}{P_a}\right)$. The bulk stress and octahedral shear stress values were calculated for each combination of corresponding confining pressure and axial cyclic stress applied during laboratory testing resulting in 15 levels of stresses for each soil sample. The substitution of k coefficient for each soil specimen and these 15 values of bulk and octahedral shear stress give 15 values of M_R for each soil specimen at different levels of stresses. This process was performed for both MODEL1 and MODEL2.

6.5.1 Verification of Prediction Model for A-1-b Soil

The laboratory M_R values and M_R values calculated from the prediction models for the A-1-b soil CT-03 and CT12 has been presented in tabular and graphical forms in Table 28 and Figure 103. CT-01 has not been included here in spite of being an A-1-b soil since it is a Material Type 1 soil but the models developed herein this report were based on Material Type 2 soils only. AASHTO - T 307 defines the Material Type 1 as soils which meet the criteria of less than 70% passing the No. 10 sieve and less than 20% passing the No. 200 sieve, and which have a plasticity index of 10 or less. Material Type 2 are the soils not meeting the criteria given for Material Type 1.

Predicted M_R values calculated from MODEL1 only has been presented in Tables 28 and Figure 103. The M_R values predicted from MODEL2 did not quite match the laboratory M_R values since the values of soil properties parameters S1_HALF and FSAND were out of the soil properties range from which MODEL2 was developed, hence requiring extrapolation which results in incredible results.

Table 28. Comparison of Laboratory and Predicted M_R values for A-1-b soils

Sample #	Lab M_R MPa	Predicted M_R MODEL1 MPa
CT-03	112	108.54
CT-03	111	102.37
CT-03	103	100.57
CT-03	98	100.23
CT-03	95	100.59
CT-03	96	89.24
CT-03	93	85.88
CT-03	89	85.69
CT-03	86	86.51
CT-03	85	87.79
CT-03	68	65.53
CT-03	67	66.02
CT-03	67	68.12
CT-03	68	70.58
CT-03	69	73.17
CT-12	104	96.39

Table 28. Comparison of Laboratory and Predicted M_R values for A-1-b soils *(Cont'd…)*

Sample #	Lab M_R MPa	Predicted M_R MODEL1 MPa
CT-12	99	92.15
CT-12	91	90.94
CT-12	86	90.78
CT-12	84	91.11
CT-12	90	82.04
CT-12	83	79.71
CT-12	77	79.68
CT-12	74	80.4
CT-12	74	81.49
CT-12	70	63.61
CT-12	64	64.22
CT-12	61	65.98
CT-12	60	68.02
CT-12	61	70.1

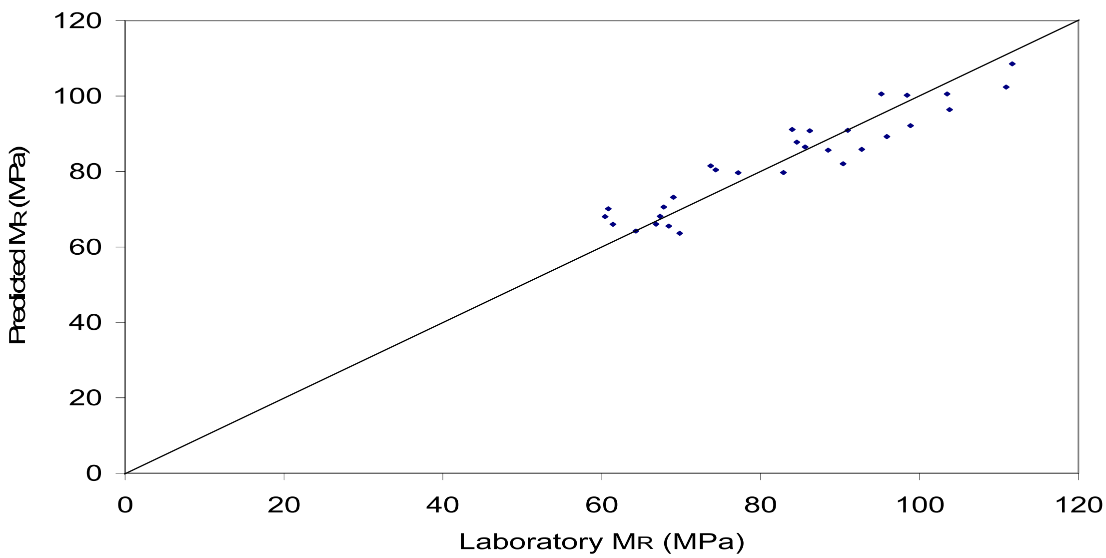


Figure 103. Predicted M_R from MODEL1 vs. Laboratory M_R for A-1-b soil samples CT-03 and CT-12

Evaluation of the M_R values shows that for MODEL1 90% of predicted M_R values were within ±10% of the laboratory M_R values and 100% of predicted M_R values were within ±20% of the laboratory M_R values.

6.5.2 Verification of Prediction Model for A-3 Soil

The laboratory M_R values and M_R values calculated from the prediction models (MODEL1 and MODEL2) for the A-3 soils CT-07, CT-08, and CT-14 have been presented in tabular and graphical forms in Table 29 and Figure 104 and 105.

Table 29. Comparison of Laboratory and Predicted M_R values for A-3 soils

Sample #	Lab M_R MPa	Predicted M_R MODEL1 MPa	MODEL2 MPa
CT-07	64	83.92	80.75
CT-07	66	80.3	77.23
CT-07	67	79.8	76.72
CT-07	71	80.38	77.24
CT-07	73	81.41	78.2
CT-07	51	65.82	63.47
CT-07	51	64.38	62.04
CT-07	54	65.33	62.92
CT-07	58	66.85	64.35
CT-07	60	68.69	66.07
CT-07	35	44.85	43.39
CT-07	36	46.42	44.86
CT-07	40	49.07	47.37
CT-07	41	51.84	50.01
CT-07	37	54.48	52.52
CT-08	67	85.49	94.62
CT-08	70	81.35	90.16
CT-08	71	80.46	89.5
CT-08	72	80.68	90.12
CT-08	74	81.48	91.43
CT-08	54	68.3	72.99
CT-08	54	66.46	71.36
CT-08	56	66.99	72.41
CT-08	59	68.19	74.19
CT-08	60	69.7	76.31
CT-08	36	47.92	48.42
CT-08	37	49.12	50.29
CT-08	40	51.49	53.4
CT-08	39	53.94	56.56
CT-08	29	56.23	59.5
CT-14	63	84.92	88.23
CT-14	66	81.28	84.3
CT-14	67	80.74	83.84
CT-14	69	81.24	84.56
CT-14	71	82.25	85.84
CT-14	49	67.32	67.98
CT-14	49	65.92	66.63
CT-14	52	66.72	67.69
CT-14	55	68.17	69.45
CT-14	57	69.95	71.57
CT-14	32	46.86	45.27
CT-14	33	48.15	46.84
CT-14	36	50.82	49.87
CT-14	38	53.51	52.92
CT-14	38	56.21	55.99

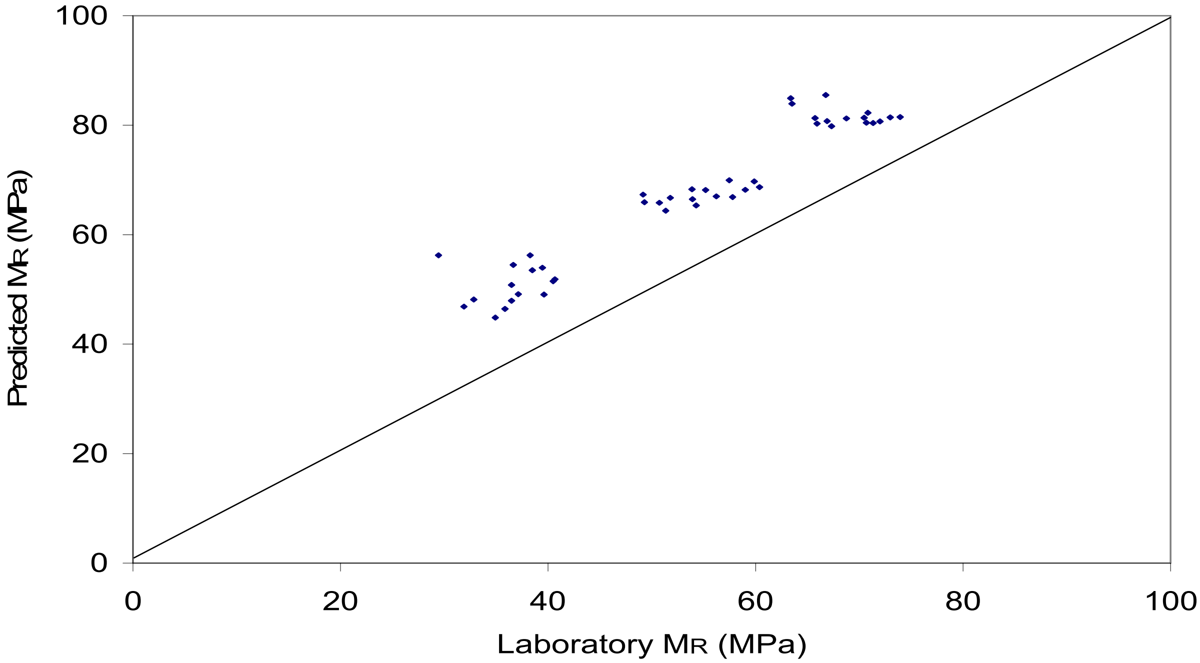


Figure 104. Predicted M_R from MODEL1 vs. Laboratory M_R for A-3 soil samples CT-07, CT-08, CT-14

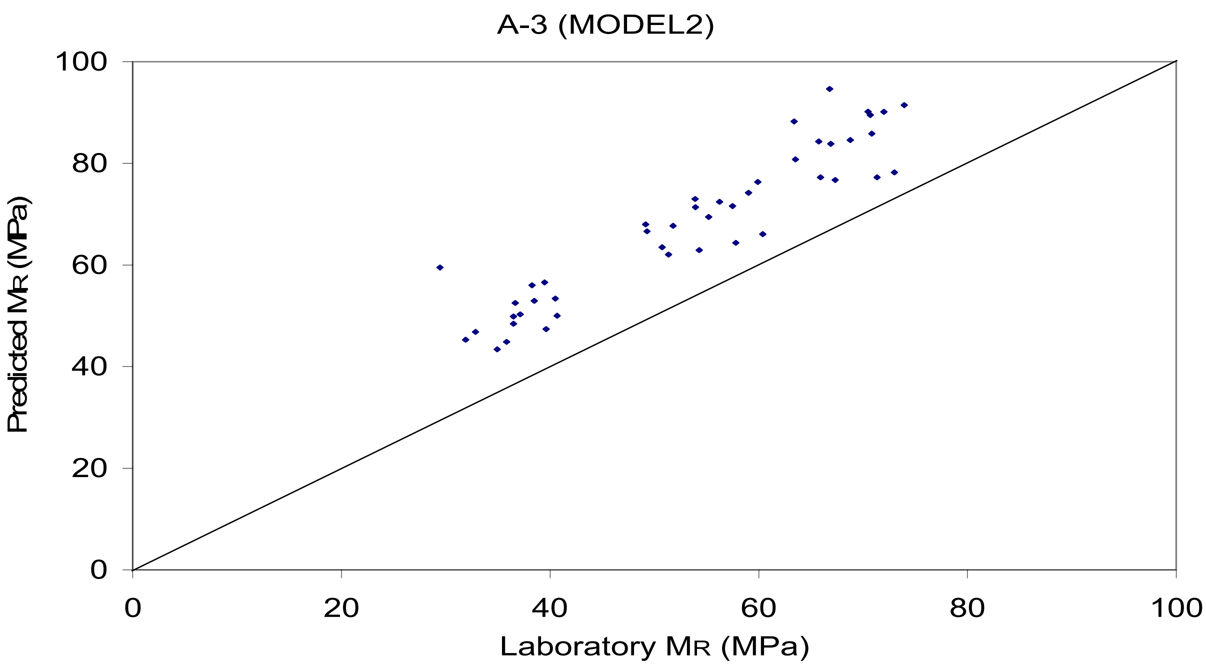


Figure 105. Predicted M_R from MODEL2 vs. Laboratory M_R for A-3 soil samples CT-07, CT-08, CT-14

Evaluation of the M_R values show 68.89% of predicted M_R were within ± 10% of the laboratory M_R values and 97.78% of predicted M_R were within ± 20% of the laboratory M_R values for MODEL1. Similarly incase of MODEL2, 6.67% of predicted M_R values were within

±10% of the laboratory M_R and 17.78% of predicted M_R values were within ± 20% of the laboratory M_R values.

6.5.3 Verification of Prediction Model for A-2-4 Soil

The laboratory M_R values and M_R values calculated from the prediction models (MODEL1 and MODEL2) for the A-2.4 soil CT-04 has been presented in tabular and graphical forms in Table 30 and Figure 106 and 107.

Table 30. Comparison of Laboratory and Predicted M_R values for A-2-4 soils

Sample #	Lab M_R MPa	Predicted M_R MODEL1 MPa	Predicted M_R MODEL2 MPa
CT-04	92	93.58	102.9
CT-04	86	73.12	80.01
CT-04	77	64.13	71.45
CT-04	74	58.81	67.21
CT-04	72	55.23	64.92
CT-04	79	80.22	67.89
CT-04	70	63.68	55
CT-04	64	56.49	50.73
CT-04	62	52.32	49.05
CT-04	62	49.58	48.52
CT-04	57	63.02	35.18
CT-04	51	51.87	31.38
CT-04	48	47.18	31.06
CT-04	48	44.57	31.75
CT-04	50	42.92	32.85

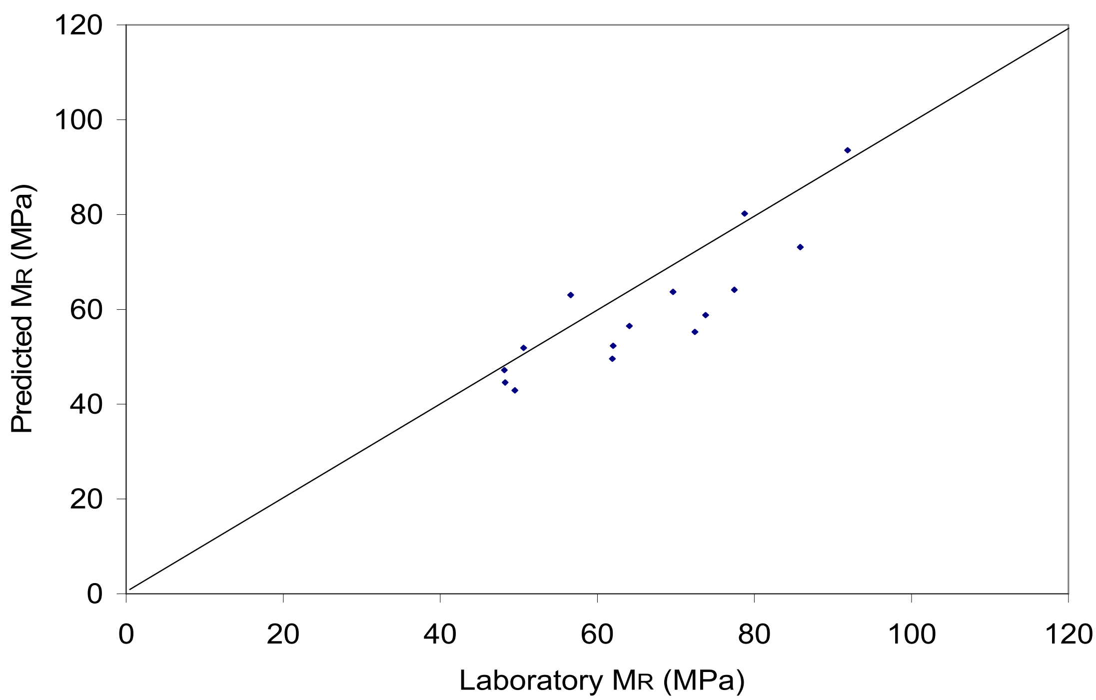


Figure 106. Predicted M_R from MODEL1 vs. Laboratory M_R for A-2-4 soil sample CT-04

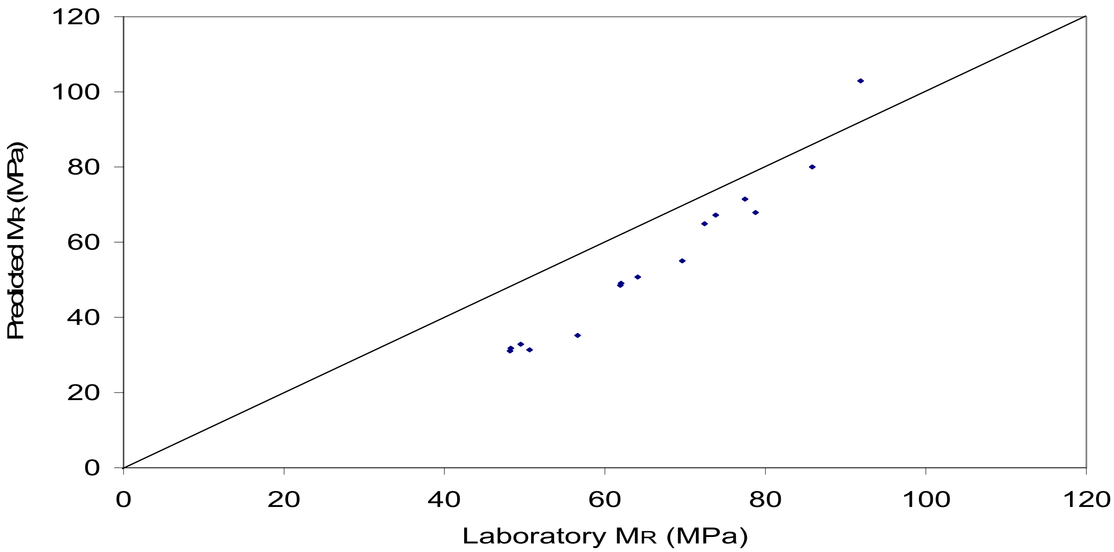


Figure 107. Predicted M_R from MODEL2 vs. Laboratory M_R for A-2-4 soil samples CT-04

Evaluation of the M_R values show that 40.0% of predicted M_R values were within ± 10% of the laboratory M_R values and 86.67% of predicted M_R values were within ± 20% of the laboratory M_R values for MODEL1. Similarly incase of MODEL2, 20.0% of predicted M_R values were within ±10% of the laboratory M_R values and 40.0% of predicted M_R values were within ± 20% of the laboratory M_R values.

6.5.4 Verification of Prediction Model for A-4 Soil

The laboratory M_R values and M_R values calculated from the prediction models (MODEL1 and MODEL2) for the A-4 soil CT-05, CT-06, CT-13, VT04- VT-05, and VT-06 have been presented in tabular and graphical forms in Table 31 and Figure 108 and 109.

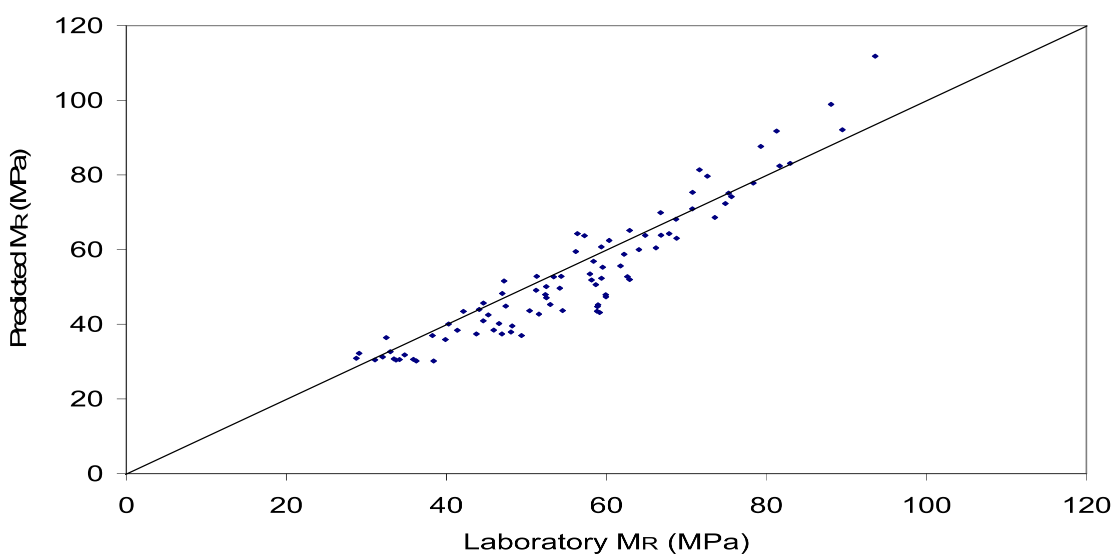


Figure 108. Predicted M_R from MODEL1 vs. Laboratory M_R for A-4 soil sample CT-05, CT-06, CT-13, VT-04, VT-05, and VT-06

Table 31. Comparison of Laboratory and Predicted M_R values for A-4 soils

Sample #	Lab M_R MPa	Predicted M_R	
		MODEL1 MPa	MODEL2 MPa
CT-05	68	64.27	73.41
CT-05	63	52.74	61.63
CT-05	60	47.92	56.48
CT-05	59	45.2	53.47
CT-05	59	43.47	51.49
CT-05	58	51.84	62.5
CT-05	50	43.59	53.46
CT-05	47	40.21	49.54
CT-05	46	38.43	47.35
CT-05	47	37.4	45.99
CT-05	38	36.99	48.56
CT-05	33	32.64	43.07
CT-05	32	31.23	41.01
CT-05	33	30.72	40.05
CT-05	36	30.59	39.58
CT-06	69	63.03	74.54
CT-06	63	51.95	63.02
CT-06	60	47.33	58.04
CT-06	59	44.75	55.16
CT-06	59	43.12	53.29
CT-06	59	50.61	62.85
CT-06	52	42.74	54.16
CT-06	48	39.55	50.47
CT-06	48	37.91	48.48
CT-06	49	37	47.31
CT-06	40	35.87	48.1
CT-06	35	31.81	43.05
CT-06	34	30.54	41.29
CT-06	36	30.17	40.6
CT-06	38	30.13	40.33
CT-13	56	64.26	74.03
CT-13	53	52.72	62.08
CT-13	52	47.96	56.96
CT-13	53	45.32	54
CT-13	55	43.63	52.05
CT-13	47	51.59	62.62
CT-13	42	43.43	53.6
CT-13	40	40.05	49.65
CT-13	41	38.37	47.56
CT-13	44	37.4	46.27
CT-13	33	36.4	47.99
CT-13	29	32.2	42.65
CT-13	29	30.88	40.72
CT-13	31	30.47	39.89
CT-13	34	30.42	39.52

Sample #	Lab M_R MPa	Predicted M_R	
		MODEL1 MPa	MODEL2 MPa
VT-04	94	111.79	116.26
VT-04	90	92.08	97.78
VT-04	83	83.09	89.37
VT-04	78	77.81	84.47
VT-04	76	74.17	81.14
VT-04	88	98.94	101.91
VT-04	82	82.43	86.78
VT-04	75	75.13	80.18
VT-04	71	70.94	76.46
VT-04	69	68.1	74.01
VT-04	72	81.37	82.57
VT-04	67	69.91	72.65
VT-04	63	65.14	68.72
VT-04	60	62.45	66.65
VT-04	59	60.7	65.38
VT-05	79	87.63	88.23
VT-05	74	68.58	68.6
VT-05	66	60.48	60.25
VT-05	62	55.6	55.21
VT-05	59	52.32	51.82
VT-05	71	75.32	76.26
VT-05	64	60	60.33
VT-05	58	53.48	53.53
VT-05	54	49.65	49.52
VT-05	53	47.09	46.82
VT-05	56	59.5	60.78
VT-05	51	49.12	49.77
VT-05	47	44.87	45.21
VT-05	45	42.48	42.61
VT-05	45	40.92	40.9
VT-06	81	91.77	89.58
VT-06	75	72.32	70.93
VT-06	67	63.83	62.73
VT-06	62	58.73	57.78
VT-06	60	55.28	54.42
VT-06	73	79.68	78.48
VT-06	65	63.79	63.07
VT-06	58	56.88	56.31
VT-06	54	52.82	52.32
VT-06	52	50.1	49.62
VT-06	57	63.73	63.66
VT-06	51	52.85	52.88
VT-06	47	48.25	48.27
VT-06	45	45.68	45.67
VT-06	44	43.97	43.92

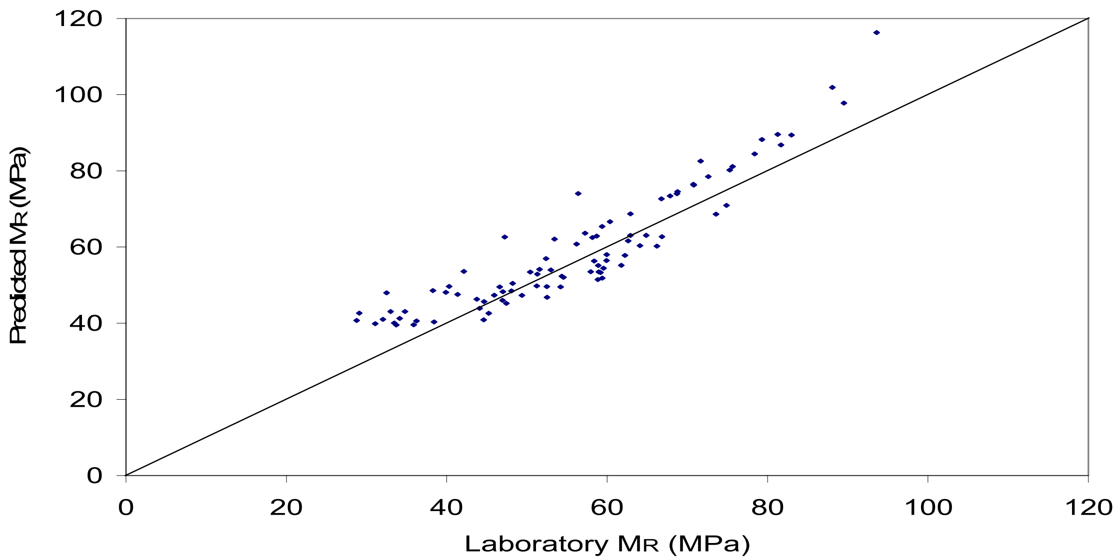


Figure 109. Predicted M_R from MODEL2 vs. Laboratory M_R for A-4 soil samples CT-05, CT-06, CT-13, VT-04, VT-05, and VT-06

Evaluation of the M_R values show that 58.89% of predicted M_R values were within ± 10% of the laboratory M_R values and 87.78% of predicted M_R values were within ± 20% of the laboratory M_R values for MODEL1. Similarly incase of MODEL2, 64.44% of predicted M_R values were within ±10% of the laboratory M_R values and 83.33% of predicted M_R values were within ± 20% of the laboratory M_R values.

6.5.5 Verification of Prediction Model for A-7-6 Soil

Prediction models for the A-7-6 soil could not be verified because both MODEL1 and MODEL2 resulted in negative values of k_2 coefficient. This may have been because the Liquid Limit and Clay percentage values are much higher than that of all the soil samples used for developing the prediction models. Attempting to use a regression equation beyond the range of the regressor variables is often inappropriate and may yield incredible answers (www.state.yale.edu). Hence prediction model for A-7-6 could not be verified.

6.6 Verification of Prediction Models developed for USCS Soil Types

The prediction models developed for the USCS soil types Coarse Grained and Fine Grained were verified by substituting the values of soil properties presented in Table 20 into the corresponding k equations presented in Sections 5.1. Value of k coefficients for the Coarse Grained soils tested have been calculated using the model developed from all coarse grained soil samples and also the model developed with samples that have CU≤100 only. k coefficients could not be calculated for soil samples CT-05, CT-06, and CT-13 because they did not have numerical value for Plasticity Index (PI=NP, Non Plastic).The value of k coefficients obtained for the different soil samples from the k coefficient equations for Coarse and Fine Grained soils have been presented in Table 32 below. The k coefficients obtained from the regression of laboratory test data have been presented in Table 27 in Section 6.5.

Table 32. Value of k coefficients calculated from the prediction models developed for USCS soil types

Sample #	log k1	k2	k3	log k1	k2	k3
	Coarse Grained (All Samples Model)			Coarse Grained (Samples with Cu≤100 Model)		
CT-01	-0.31708	0.69611	-0.17518	-0.31153	0.70709	-0.16573
CT-03	-0.08449	0.60395	-0.23383	-0.35671	0.65669	-0.17779
CT-04	-0.24354	0.59819	-0.25399	-0.37113	0.64556	-0.20192
CT-12	-0.02571	0.62046	-0.22433	-0.34926	0.65380	-0.16628
CT-07	-0.33359	0.66499	-0.12026	-0.33842	0.68866	-0.11077
CT-08	-0.33352	0.66025	-0.12015	-0.31398	0.67245	-0.09823
CT-14	-0.32949	0.67409	-0.11562	-0.32731	0.68882	-0.10375
	Fine Grained					
VT-01	-0.69163	-0.13393	-0.29295			
VT-02	-0.75853	-0.10989	-0.30669			
VT-03	-0.73022	-0.11758	-0.28733			
VT-04	-0.38594	0.36196	-0.23965			
VT-05	-0.56951	0.38657	-0.32199			
VT-06	-0.53683	0.38572	-0.30654			

6.6.1 Verification of Prediction Model for USCS Soil Type: Coarse Grained (All Samples)

M_R values were predicted by substituting k coefficients presented in Table 32 into Eq. (5). The plot for the predicted and laboratory measured M_R has been presented in Figure 110. Detail numerical values of laboratory and predicted M_R can be found in Table 33. Analysis of the predicted and laboratory M_R shows that 8.74% of predicted M_R falls within ± 10% of laboratory M_R and 32.04% of predicted M_R falls within ± 20% of laboratory M_R. The values of M_R for soil samples CT-03, CT-04, and CT-12 which had CU>100 were not accurately predicted by the prediction models.

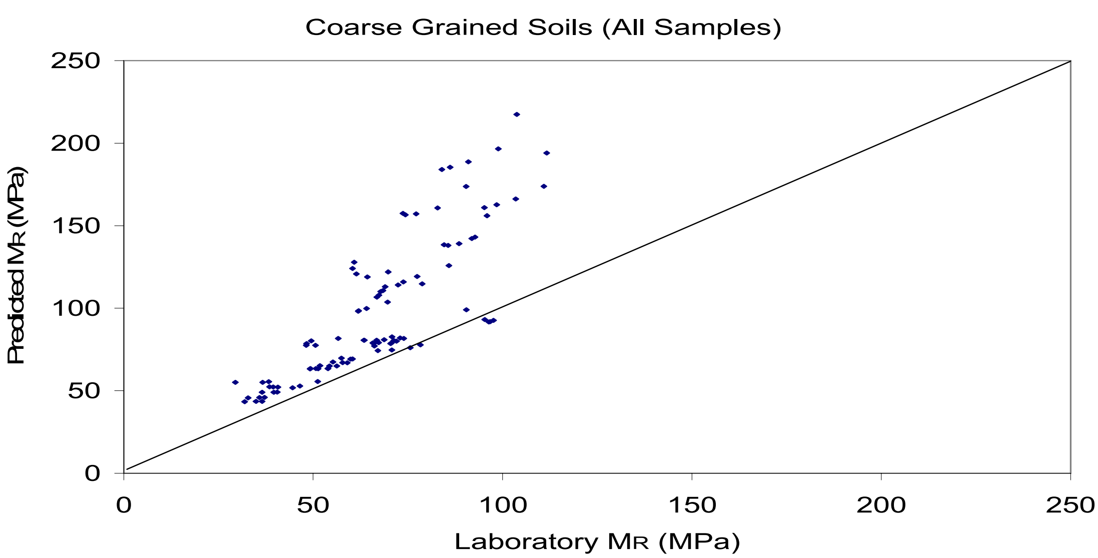


Figure 110. Predicted M_R vs. Laboratory M_R for Coarse grained soils (Model with all samples used for predicted M_R)

6.6.2 Verification of Prediction Model for USCS Soil Type: Coarse Grained (Samples with CU≤100)

M_R values were predicted by substituting k coefficients presented in Table 32 into Eq. (5). Plot for predicted M_R calculated using prediction models developed from coarse grained soil samples that have CU≤100 and laboratory M_R has been presented in Figure111. Detail numerical values of laboratory and predicted M_R can be found in Table 33. Evaluation of the M_R values show that 22.33% of predicted M_R values were within ± 10% of the laboratory M_R values and 68.93% of predicted M_R values were within ± 20% of the laboratory M_R values.

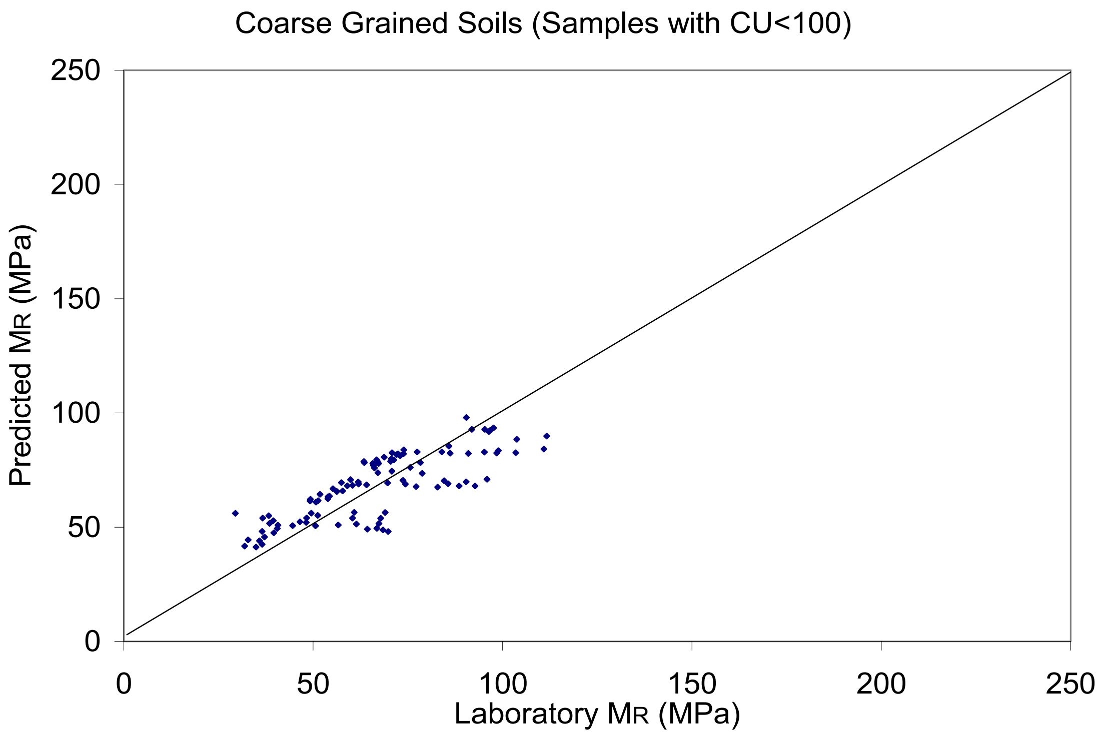


Figure 111. Predicted M_R vs. Laboratory M_R for Coarse grained soils (Model with all samples that had CU≤100 used for predicted M_R)

Table 33. Comparison of Laboratory and Predicted M_R values for Coarse Grained soils

Sample #	Lab M_R MPa	Predicted M_R	
		From Model with all samples MPa	From Model with samples that had CU≤100 MPa
CT-01	90	99.05	97.98
CT-01	95	93.13	92.81
CT-01	96	91.74	91.86
CT-01	97	91.86	92.31
CT-01	98	92.66	93.37
CT-01	66	77.12	75.97
CT-01	67	74.35	73.82
CT-01	71	74.65	74.5
CT-01	76	75.99	76.13
CT-01	78	77.77	78.15
CT-01	45	51.78	50.69
CT-01	47	52.92	52.27
CT-01	51	55.55	55.18
CT-04	92	142.24	92.75
CT-04	86	125.84	85.4
CT-04	77	119.2	82.91
CT-04	74	115.86	82.09
CT-04	72	114.07	82.04
CT-04	79	114.74	73.55
CT-04	70	103.68	69.27
CT-04	64	99.87	68.49
CT-04	62	98.46	68.86
CT-04	62	98.14	69.74
CT-04	57	81.68	50.91
CT-04	51	77.57	50.59
CT-04	48	77.5	52.06
CT-04	48	78.64	54
CT-04	50	80.22	56.09

Sample #	Lab M_R MPa	Predicted M_R	
		From Model with all samples MPa	From Model with samples that had CU≤100 MPa
CT-03	112	194.06	89.85
CT-03	111	173.91	84.12
CT-03	103	166.22	82.57
CT-03	98	162.67	82.39
CT-03	95	160.99	82.88
CT-03	96	156.04	70.9
CT-03	93	143.08	68.01
CT-03	89	139.1	68.03
CT-03	86	138.08	68.95
CT-03	85	138.37	70.29
CT-03	68	110.68	48.79
CT-03	67	106.79	49.47
CT-03	67	107.8	51.52
CT-03	68	110.11	53.89
CT-03	69	112.99	56.38
CT-12	104	217.45	88.43
CT-12	99	196.55	83.45
CT-12	91	188.73	82.24
CT-12	86	185.34	82.3
CT-12	84	184.01	82.96
CT-12	90	173.77	69.82
CT-12	83	160.68	67.47
CT-12	77	157.1	67.75
CT-12	74	156.57	68.88
CT-12	74	157.53	70.43
CT-12	70	122.01	48.08
CT-12	64	118.99	49.14
CT-12	61	120.84	51.37
CT-12	60	124.08	53.9
CT-12	61	127.79	56.48

Table 33. Comparison of Laboratory and Predicted M_R values for Coarse Grained soils *(Cont'd…)*

Sample #	Lab M_R MPa	Predicted M_R: From Model with all samples MPa	Predicted M_R: From Model with samples that had CU≤100 MPa
CT-07	64	80.62	78.17
CT-07	66	78.74	77.01
CT-07	67	79.15	77.85
CT-07	71	80.38	79.42
CT-07	73	81.89	81.21
CT-07	51	63.44	60.96
CT-07	51	63.37	61.5
CT-07	54	65.01	63.49
CT-07	58	67.05	65.82
CT-07	60	69.29	68.3
CT-07	35	43.54	41.29
CT-07	36	45.93	44.05
CT-07	40	49.07	47.45
CT-07	41	52.21	50.79
CT-07	37	55.15	53.92
CT-08	67	80.57	79.48
CT-08	70	78.59	78.8
CT-08	71	78.95	79.95
CT-08	72	80.09	81.68
CT-08	74	81.66	83.76
CT-08	54	63.5	62.37
CT-08	54	63.43	63.35
CT-08	56	65.01	65.6
CT-08	59	67	68.11
CT-08	60	69.18	70.74
CT-08	36	43.58	42.48
CT-08	37	46	45.65
CT-08	40	49.16	49.33
CT-08	39	52.23	52.83
CT-08	29	55.03	56

Sample #	Lab M_R MPa	Predicted M_R: From Model with all samples MPa	Predicted M_R: From Model with samples that had CU≤100 MPa
CT-14	63	80.61	78.68
CT-14	66	78.97	77.82
CT-14	67	79.57	78.87
CT-14	69	80.92	80.57
CT-14	71	82.63	82.58
CT-14	49	63.25	61.4
CT-14	49	63.44	62.21
CT-14	52	65.2	64.36
CT-14	55	67.38	66.82
CT-14	57	69.77	69.46
CT-14	32	43.31	41.69
CT-14	33	45.69	44.47
CT-14	36	49.06	48.12
CT-14	38	52.32	51.59
CT-14	38	55.51	54.98

6.6.3 Verification of Prediction Model for USCS Soil Type: Fine Grained

M_R values were predicted by substituting k coefficients for fine grained soil presented in Table 32 into Eq. (5). Plot for predicted M_R against laboratory M_R has been presented in Figure 112. Numerical values of laboratory and predicted M_R can be found in Table 34. Evaluation of the M_R values show that 37.78% of predicted M_R values were within ± 10% of the laboratory M_R values and 54.44% of predicted M_R values were within ± 20% of the laboratory M_R. The M_R values for soil samples VT-01, VT-02, VT-03 which had PI and LL values much higher than the

PI and LL values used in developing prediction models had larger error values, hence warning against extrapolation.

Table 34. Comparison of Laboratory and Predicted M_R values for Fine Grained soils

Sample #	Lab M_R MPa	Predicted M_R MPa
VT-01	70	45.56
VT-01	69	36.77
VT-01	65	32.34
VT-01	61	29.48
VT-01	58	27.38
VT-01	65	47.86
VT-01	64	38.43
VT-01	61	33.68
VT-01	58	30.6
VT-01	56	28.32
VT-01	50	51.76
VT-01	53	41.12
VT-01	54	35.69
VT-01	53	32.2
VT-01	52	29.66
VT-02	61	40.9
VT-02	59	32.77
VT-02	55	28.78
VT-02	52	26.17
VT-02	48	24.28
VT-02	57	42.59
VT-02	56	33.98
VT-02	54	29.74
VT-02	51	26.99
VT-02	49	24.95
VT-02	44	45.5
VT-02	45	36.01
VT-02	44	31.23
VT-02	44	28.17
VT-02	43	25.94
VT-03	66	41.18
VT-03	64	33.49
VT-03	61	29.57
VT-03	57	27.02
VT-03	55	25.14
VT-03	61	43.05
VT-03	60	34.8
VT-03	57	30.63
VT-03	54	27.9
VT-03	52	25.9
VT-03	50	46.06
VT-03	51	36.93
VT-03	50	32.24
VT-03	49	29.2
VT-03	48	26.99
VT-04	94	91.6
VT-04	90	80.09
VT-04	83	74.86
VT-04	78	71.87
VT-04	76	69.88
VT-04	88	80.48
VT-04	82	71.24
VT-04	75	67.3
VT-04	71	65.17
VT-04	69	63.83
VT-04	72	65.46
VT-04	67	59.83
VT-04	63	57.83
VT-04	60	56.94
VT-04	59	56.53

Table 34. Comparison of Laboratory and Predicted M_R values for Fine Grained soils *(Cont'd…)*

Sample #	Lab M_R MPa	Predicted M_R MPa
VT-05	79	76.45
VT-05	74	63.18
VT-05	66	57.41
VT-05	62	53.89
VT-05	59	51.53
VT-05	71	66.51
VT-05	64	55.86
VT-05	58	51.25
VT-05	54	48.55
VT-05	53	46.76
VT-05	56	53.5
VT-05	51	46.42
VT-05	47	43.58
VT-05	45	42.03
VT-05	45	41.08

Sample #	Lab M_R MPa	Predicted M_R MPa
VT-06	81	78.93
VT-06	75	66
VT-06	67	60.25
VT-06	62	56.79
VT-06	60	54.46
VT-06	73	68.68
VT-06	65	58.31
VT-06	58	53.78
VT-06	54	51.15
VT-06	52	49.43
VT-06	57	55.12
VT-06	51	48.42
VT-06	47	45.71
VT-06	45	44.31
VT-06	44	43.46

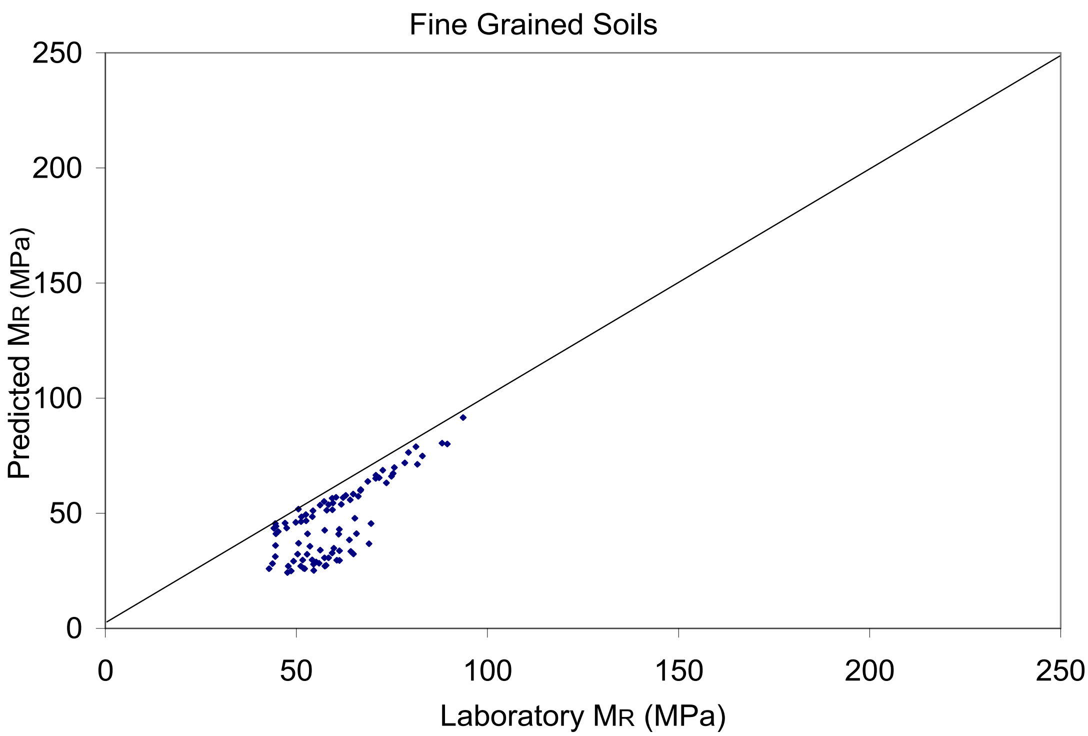


Figure 112. Predicted M_R vs. Laboratory M_R for Fine grained soils

7. SUBGRADE SUPPORT VALUES FROM FALLING WEIGHT DEFLECTOMETER TESTS

Subgrade modulus value can be determined with the help of Nondestructive tests like the Falling Weight Deflectometer (FWD) test. Several mechanical devices, such as the Dynaflect, the Road Rater and the Falling Weight Deflectometer (FWD), are available to assess pavement integrity. Among the available mechanical devices, field studies (Hoffman and Thompson 1982) have shown that the FWD yields good correlations with pavement deflections induced by traffic loading. The FWD applies a transient load to the pavement, which accords better with reality and, thereby, models moving wheel loads rather better than the Dynaflect or the Road Rater, which impart vibratory loads to the surface of the pavement. The fundamental concept behind the evaluation of subgrade modulus from FWD test and the analysis of FWD test results for the Long Term Pavement Performance (LTPP) tests have been discussed in the subsequent sections.

7.1 Falling Weight Deflectometer (FWD) Test and the Backcalculated Modulus

A Falling Weight Deflectometer (FWD) device essentially consists of a large mass that is constrained to fall vertically under gravity on to a spring loaded plate resting on the pavement surface. Figure 113 shows a schematic of a typical pavement structure tested under a FWD device. The height through which the mass that drops can be changed. The change in height produces different impact loads which can be used to simulate a range of typical wheel loads with the same apparatus. Deflection measurements can be taken at the center of the loaded area and a number of stations outside the loaded area by means of suitable geophones (Sebaaly et al. 1985).

When the load is applied, it spreads through a portion of the pavement system as represented by the conical zone in the figure. The inclination of the sides of this zone which is varying from layer to layer is related to the relative stiffness or modulus of the material in each layer. The stress is spread over a larger area for stiffer material (larger modulus). Surface deflection measured at or beyond the radial distance a_{3e} (interface of the subbase and subgrade layer) is due to stresses (deformations) within the subgrade only. Hence the outer readings of deflection basin primarily reflect the insitu modulus properties of the lower (subgrade) soil (AASHTO 1993).

Backcalculation technique is used to estimate the modulus values from the measured deflection basin results. Backcalculation takes a measured surface deflection and attempts to match it with a calculated surface deflection generated from an identical pavement structure using assumed layer stiffnesses/moduli. The assumed layer moduli are adjusted until they produce a surface deflection that closely matches the measured deflection. The combination of assumed layer stiffeness that results in the close match is taken to be near the actual insitu moduli for the various pavement layers. This process is generally iterative and is performed with the help of a suitable backcalcualtion software package.

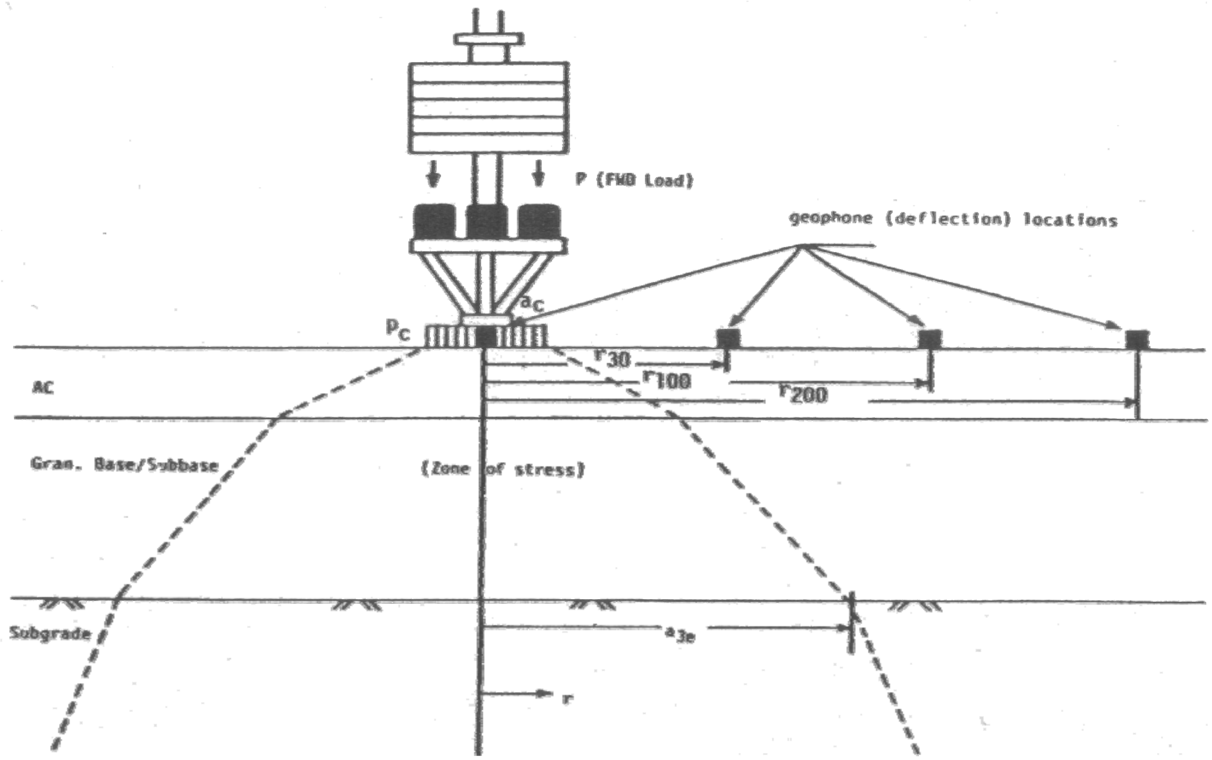


Figure 113. Schematic of Stress Zone within Pavement Structure under the FWD Load (AASHTO 1993)

7.2 Comparison of Laboratory Resilient Modulus (M_R) and FWD Backcalculated Modulus

To correlate the laboratory resilient modulus (M_R) values and FWD backcalculated modulus (E (FWD)) values, the test data for 20 states in the United States and 2 Provinces in Canada within the 4 regions, namely, New England, Northern Mid Atlantic, Great Lakes and Upper Mid West, was extracted from Long Term Pavement Perfromance (LTPP) Information Management System (IMS) Data, Release 15, January 2003 Upload. All raw data extracted from LTPP database has been presented in Appendix I (available in CD). The LTPP test sites where Laboratory resilient modulus (M_R) and field (FWD) tests are available have been presented in Appendix B, Table B.1. In the table, the test sites where both the M_R and FWD data were collected by the LTPP program are shown in bold type face. SHRP ID in the table is the test section identification number assigned by the LTPP program. It must be combined with State Code to be unique. Generally, the field test sections are 152 meter long with a 15.2 meter materials sampling section at each end. For each drop of the mass, deflections were recorded at 7 points to get the deflection bowl. FWD Backcalculated modulus data for Rhode Island is not available in the LTPP database. Mean Elastic Modulus has been calculated using Backcalculation software MODCOMP v 4.2.

For the comparison purpose herein, an average of FWD backcalculated elastic modulus values corresponding to different levels of drop heights was calculated to obtain a single modulus value for the subgrade soil at a particular test section. They are given in Appendix H,

Table H.3.1 through Table H.3.4. Ranges of the E(FWD) to M_R ratios at each of the 3 levels of confining pressures for various AASHTO soil types found in the 4 regions (20 states in the U.S. and 2 Provinces in Canada) are presented in Table H.1 in Appendix H. Also, the ranges of the E (FWD) to M_R ratios by AASHTO soil types for each of the 20 individual states in the U.S. and 2 Provinces in Canada are given in Tables H.2, H.3, H.4 in Appendix H. Resilient modulus (M_R) value considered for Tables H.2, H.3, H.4 are average M_R values at confining pressures of 13.8 kPa, 27.6 kPa and 41.4 kPa respectively during laboratory testing. However, the backcalculated modulus values used for calculating the ratio in Tables H.2, H.3, H.4 are the same for all 3 tables.

In general, it was observed that the backcalculated modulus values were higher than the laboratory resilient modulus values conducted at the same test site. However, these ratios are not showing a definite relationship between the two values. This may be because though at the same test site, the year of FWD testing and lab specimen sampling are different, the moisture content and density during these two tests may be different, etc. Furthermore, since M_R depends on soil and stress conditions, calculating the ratio E(FWD)/Lab M_R under different lab stress conditions against a single field stress condition may have resulted inaccurate values of ratios.

A better approach would have been to calculate the M_R using bulk and octahedral stresses at the depth of representative subgrade D where the stress ratio (normal stress at the pavement surface / the normal stress at the depth, D) is less than or equal to 0.1 and compare this M_R with the backcalculated M_R. Knowing the k coefficients for each type of soil for each LTPP site, the bulk and octahedral stresses at D, M_R can be calculated using Eq. (2). Due to the unavailability of data on field stress conditions, this approach could not be used.

8. SUMMARY AND CONCLUSIONS

The main objective of this research project was to establish subgrade support (resilient modulus) values for typical soils in New England. To accomplish this goal, various publications and database were used. These include United States Department of Agriculture (USDA) Soil Survey reports, Long Term Pavement Performance Information Management System (LTPP IMS) database, Transportation Research Information Services (TRIS) database and several other reports and journal articles.

From the thorough review of USDA soil survey reports, we identified the major soil types found in the New England States. These include A-1, A-2, A-3, A-4, A-5, A-6 and A-7 soil types. Connecticut has A-2 and A-4, Maine has A-1, A-2, A-3, A-4 A-5 and A-6, Massachusetts has A-1, A-2, A-3, A-4, A-5 and A-6, New Hampshire has A-1, A-2 and A-4, Vermont has A-1, A-2, A-4, A-6 and A-7 as the predominant soil types. The predominant soil type in Rhode Island could not be identified because the soil type for only the entire state has been given but not county wise.

The data collected on laboratory resilient modulus tests for about 300 LTPP test sites in 21 different states from LTPP IMS database show that the resilient modulus value generally increases with the increase in confining pressure during the test for the AASHTO soil types A-1-b, A-3, A-2-4, A-4, A-6 and A-7-6. Soil types A-1-a, A-2-5, A-2-7, A-5 and A-7-5 were not present in the test sites considered for this study. It was observed that for the granular soils like A-1-b, A-3, and A-2-4, M_R usually increased with increase in nominal maximum axial stress at the same level of confining pressure while for silty-clay soils like A-4, A-6, and A-7-6 there was a general trend of decrease in M_R with increase in nominal maximum axial stress at the same level of confining pressure. Observation of M_R values for the test sites considered from LTPP IMS database show that for A-1-b soils, the majority of M_R values were in the range of 50 to 110 MPa. Likewise, for A-3 soils the range is 50 to 110 MPa, for A-2-4 soils the range is 50 to 120 MPa, for A-2-6 soils the range is 50 to 120 MPa, for A-4 soils the range is 30 to 150, for A-6 soils the range is 30 to 160 MPa and for A-7-6 soils, the range is 20 to 150 MPa. It was observed that the minimum resilient modulus values obtained for A-1-b, A-3, A-2-4 soils were higher than the minimum values for A-4, A-6 and A-7-6 soils.

Generalized constitutive model that relates resilient modulus (M_R) with the bulk stress and octahedral shear stress was considered for predicting the subgrade M_R by developing regression equations for the k coefficients in the model. The regression equations relate the k coefficients to the soil properties which makes the prediction of M_R possible based on these basic soil properties at known stress states. Prediction models for the k coefficients in the generalized constitutive model were developed for AASHTO soil types A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6 using multiple linear regression technique. The data used for model development were collected from LTPP IMS database for 259 test specimens collected from test sites in 21 states including 3 New England states, 16 nearby states in the U.S. and 2 provinces in Canada. Three prediction models have been developed for each AASHTO soil type. The first set of model is the composite model that has been developed from all reconstituted soil specimens, the second set of models have been developed from only those samples that had been compacted at the optimum moisture content during M_R testing and the third model set of models have been developed from the samples that had been compacted at insitu moisture content. In the regression analysis, the multiple correlation coefficient (R^2), adjusted R^2, Variance Inflation Factor (VIF) and the consideration of relevant soil physical properties were the criteria used for selecting an appropriate model for the k coefficients. Summary of the prediction models developed are presented in Table 35 through Table 40. The R^2 values obtained for the prediction models for k coefficients relating to the soil properties lie between 0.30 and 0.99. Descriptive statistics that compare the prediction models with the measured data are summarized in Table 42.

Furthermore, the data collected from LTPP database were classified according to Unified Soil Classification System into Coarse Grained and Fine Grained soils and prediction models were developed for each type. Summary of the prediction models developed for the USCS soil types are presented in Table 41. The R^2 values for the models ranged from 0.22 to 0.63. Descriptive statistics that compare the prediction models with the measured data are summarized in Table 42.

Some R^2 values are not as high as reported in some of the previous studies since the data extracted from the LTPP database for this study covered varied and wide locations. Also, the resilient modulus tests in the LTPP database were not performed in a single laboratory. This introduces high possibility of variations in the measure data due to equipment/operator variability. Since the models in this study were developed from a large number of samples covering 19 different states in the U.S. and 2 provinces in Canada, these models should be applicable to a wider geographic region.

The results from the laboratory M_R tests conducted on representative New England subgrade soils show that for both AASHTO and USCS soil type categories, the M_R values obtained from the prediction models developed in this study matched reasonably well in general, and in some case quite close, to the experimental values. The descriptive statistics showing the comparison between the M_R values from the prediction models and that from the laboratory tests have been summarized in Table 43.

It was observed that extrapolating beyond the range of predictor variables yielded large errors between the predicted and laboratory M_R values. Therefore, care should be taken while using the developed prediction models to predict M_R values of new samples so as to avoid extrapolation beyond the values of predictor variables used in developing the models.

In general, the FWD backcalculated values obtained from LTPP IMS database were observed to be higher than the laboratory resilient modulus values at the same site. However, a definite relationship between these two values could not be observed due to large variations in the FWD backcalculated modulus values and the lack of data of these two types of tests performed under similar conditions of moisture, density, and season and data on field stress.

Table 35. Summary of second step regression for A-1-b soils

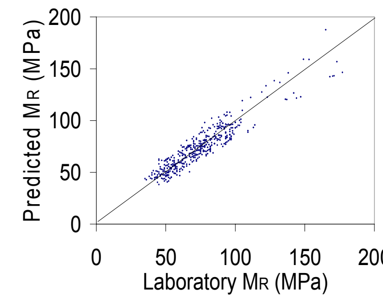
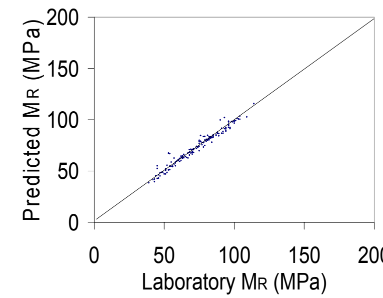
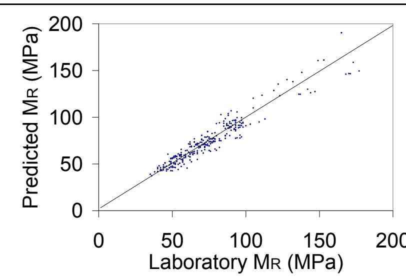
Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-1-b	MODEL1	All samples	29 (12)	log_k1 = 0.09931 - 0.00743 x MC + 0.00009293 x DD + 0.00505 x LL - 0.00466 x S3_8 - 0.01157 x SN200	0.57	0.47	Pr>|t| = 0.83, 0.20, 0.67 for MC, DD, LL resp.	
				k2 = -0.86401 - 0.01884 x OMC - 0.00116 x DD + 2.01898 x DDR + 0.02548 x S1 - 0.00691 x SN10 - 0.01047 x SN80 + 0.03127 x SILT	0.68	0.58	VIF=10.5 for SN80	
				k3 = -0.74756 - 0.00913 x MC - 0.00041464 x DD - 0.00472 x PL + 0.03540 x S3 - 0.02075 x S2	0.55	0.46	Pr>|t| = 0.21 for intercept	
	MODEL2	Samples compacted near to OMC only	10 (6)	log_k1 = -9.85454 - 0.01714 x OMC - 0.00078852 x DD + 0.11588 x S1_HALF - 0.00616 x SN10 + 0.00279 x FSAND	0.99	0.97		
				k2 = -1.15403 + 0.03198 x OMC + 5.69990 x DDR - 0.04336 x S1_HALF + 0.01404 x SN40 + 0.00476 x CSAND - 0.00649 x FSAND	0.99	0.98		
				k3 = 0.22460 - 0.02071 x OMC - 0.00010179 x MAXDD - 0.00046354 x SN10 - 0.00682 x SN40 + 0.00936 x FSAND	0.99	0.99		
	MODEL3	Samples compacted near to insitu MC only	19(7)	log_k1 = 1.78349 - 0.03097x MC + 0.00772 x LL - 0.01837 x S1_HALF - 0.01154 x SN200	0.71	0.63		
				k2 = - 3.99018 - 0.06842 x MC + 0.49482 x MCR - 0.00185 x DD + 2.83862 x DDR + 0.06019 x S2 - 0.00774 x SN10 + 0.02423 x SILT	0.8	0.67		
				k3 = - 1.17525 - 0.01956 x MC - 0.00702 x PL + 0.02351 x S3 - 0.01190 x S1_HALF	0.6	0.49		
$M_R = k1 \times Pa\,(\theta/Pa)^{k2}\,(\tau_{oct}/Pa)^{k3}$								

Table 36. Summary of second step regression for A-3 soils

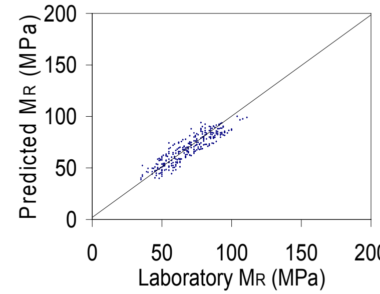
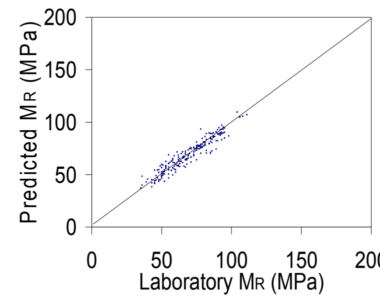
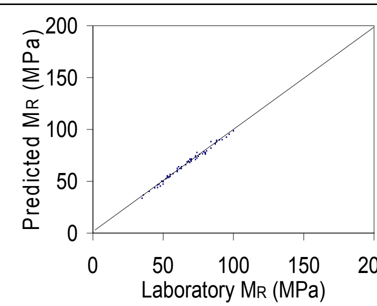
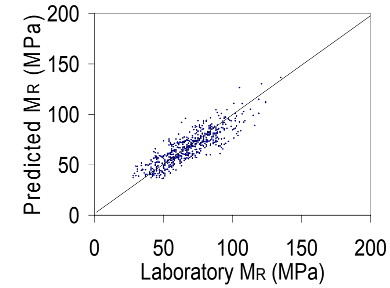
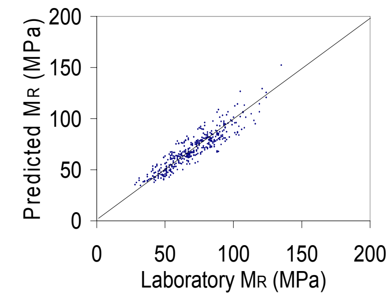
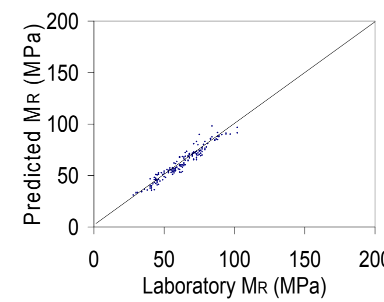
Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-3	MODEL1	All samples	19 (11)	log_k1 = - 0.93681 - 0.01248 x MC + 0.30352 x MCR + 0.00020285 x DD + 0.00194 x FSAND	0.47	0.32	Pr>|t|=0.24 for DD	
				k2 = - 0.13234 - 0.01724 x MC + 0.02560 x OMC + 0.00032543 x DD + 0.00313 x SN40 - 0.00291x SN80 - 0.01843 x CLAY	0.58	0.38	Pr>|t|=0.82 & 0.28 for intercept & DD	
				k3 = - 1.03002 + 0.09865 x MCR + 0.00032615 x DD + 0.00220 x S1_HALF + 0.00067403 x SN40	0.76	0.69		
	MODEL2	Samples compacted near to OMC only	14 (10)	log_k1 = -1.28763 - 0.01554 x OMC - 1.59688 x DDR + 0.04783 x S1 - 0.02146 x S3_4 + 0.00124 x SN80	0.72	0.55	Pr>|t|=0.35 for intercept	
				k2 = -5.81794 + 0.00420 x OMC + 0.42100 x MCR - 2.53496 x DDR + 0.06786 x S1_HALF + 0.01649 x S3_4	0.8	0.67	Pr>|t|=0.26, 0.36 & 0.18 for OMC, MCR & S3_4 resp.	
				k3 = - 0.78512 + 0.00270 x OMC + 0.00032286 x DD + 0.04002 x S1_HALF - 0.04000 x S1 + 0.00119 x SN40 - 0.00077438 x SN80 + 0.00446 x SILT	0.99	0.98		
	MODEL3	Samples compacted near to insitu MC only	4 (3)	log_k1 = - 1.80028 + 0.06083 x MC + 0.09612 x OMC	0.99	0.99	Only 4 samples, models to be used with caution	
				k2 = 1.11468 - 0.03964 x MC - 0.04803 x CLAY	0.98	0.94		
				k3 = 1.89076 - 0.08899 x OMC - 0.00055406 x MAXDD	0.99	0.99		
$M_R = k1 \times Pa\,(\theta / Pa)^{k2}\ (\tau_{oct} / Pa)^{k3}$								

Table 37. Summary of second step regression for A-2-4 soils

Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-2-4	MODEL1	All samples	40 (13)	log_k1 = 1.10795 - 0.02889 x OMC - 0.23628 x MCR - 0.67002 x DDR - 0.01701 x S2 + 0.01405 x S3_4	0.37	0.28		
				k2 = - 0.69772 + 0.02106 x MC + 0.00054260 x DD - 0.00657 x LL + 0.00293 x SN10 - 0.00460 x SN200	0.58	0.51		
				k3 = 0.50825 - 0.01956 x OMC - 0.07234 x MCR - 0.00492 x LL - 0.00652 x S2 + 0.00384 x SN40 - 0.00153 x SN80 + 0.00344 x CLAY	0.69	0.63		
	MODEL2	Samples compacted near to OMC only	28 (12)	log_k1 = 2.01010 - 0.06696 x OMC + 0.00057415 x DD - 0.00095144 x MAXDD - 0.04473 x S2 + 0.03673 x S1 - 0.00355 x CSAND	0.59	0.48	Pr>|t|=0.21 for CSAND	
				k2 = 2.05743 + 0.02542 x OMC - 2.57064 x DDR + 0.08047 x S2 - 0.09125 x S1 + 0.01852 x S3_8 - 0.00776 x SN200 + 0.01014 x CSAND	0.78	0.7		
				k3 = 1.79954 - 0.05488 x MC - 0.00061034 x MAXDD - 0.00592 x LL - 0.00917 x S2 + 0.00751 x S1_2 - 0.00288 x CSAND + 0.00440 x CLAY	0.86	0.81		
	MODEL3	Samples compacted near to insitu MC only	12 (6)	log_k1 = 1.05873 - 0.13450 x MCR + 0.00045768 x MAXDD - 0.00905 x LL - 0.02172 x S3 + 0.00269 x SN80 - 0.00982 x SILT	0.99	0.98		
				k2 = - 1.58669 + 0.01953 x OMC + 0.00036406 x DD + 0.01688 x S1_2 - 0.00949 x SN80 - 0.01289 x CSAND + 0.02220 x SILT	0.99	0.97		
				k3 = - 1.26595 + 0.01043 x MC + 0.00070217 x DD - 0.01068 x SN200 - 0.00971 x CSAND	0.79	0.66		

$M_R = k1 \times Pa\ (\theta / Pa)^{k2}\ (\tau_{oct} / Pa)^{k3}$

Table 38. Summary of second step regression for A-4 soils

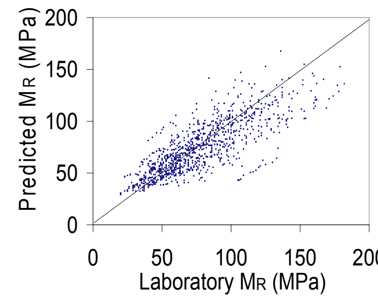
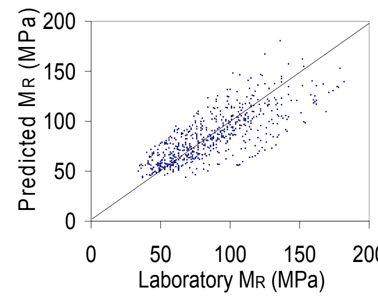
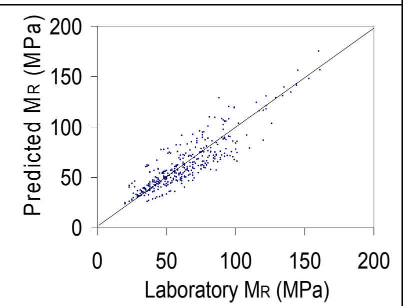
Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-4	MODEL1	All samples	66 (15)	log_k1 = 5.74999 - 0.13693 x OMC - 0.79256 x MCR - 0.00161 x MAXDD - 0.01092 x S1 + 0.00591 x SN200 + 0.00774 x CLAY	0.52	0.47	Pr>|t|=0.17 for S1	
				k2 = - 0.74402 + 0.03585 x MC + 0.00048034 x DD + 0.00641 x PL - 0.00839 x LL + 0.00484 x SN10 - 0.00477 x SN80 - 0.00994 x CLAY	0.54	0.48	Pr>|t|=0.17 for PL	
				k3 = 1.30193 - 0.0267 x MC - 0.02764 x OMC - 0.00063254 x MAXDD + 0.00156 x SN10 + 0.00253 x SILT	0.3	0.24	Pr>|t|=0.24 for SN10	
	MODEL2	Samples compacted near to OMC only	41 (13)	log_k1 = 3.60888 - 0.13212 x MC - 0.00161 x MAXDD + 0.02140 x S1_HALF - 0.01936 x S3_4 + 0.00790 x SN200	0.52	0.45		
				k2 = -3.29043 + 0.05316 x OMC + 0.00126 x DD - 0.00468 x PL + 0.01264 x S1 - 0.00819 x CSAND - 0.00295 x SILT - 0.01365 x CLAY	0.68	0.62		
				k3 = 1.93886 - 0.05933 x MC - 0.00074630 x MAXDD - 0.00271x SN80 - 0.01004 x CSAND + 0.00420 x SILT	0.5	0.43	Pr>|t|=0.20 for SN80	
	MODEL3	Samples compacted near to insitu MC only	25 (9)	log_k1 = 12.04783 - 0.06409 x MC - 0.06928 x OMC - 0.00152 x MAXDD - 0.12972 x S1 + 0.04723 x S3_8 + 0.02535 x CLAY	0.7	0.6		
				k2 = 1.55793 - 0.00018031 x DD + 0.01067 x PL - 0.03284 x S3_8 + 0.04736 x SN10 - 0.02589 x SN80 - 0.02342 x CSAND	0.77	0.69	Pr>|t|=0.36 for DD	
				k3 = 3.18908 - 0.02399 x MC - 0.05290 x S1 + 0.02136 x SN4 + 0.00317 x CLAY	0.42	0.3	Pr>|t|=0.19, 0.33 for intercept, CLAY resp.	
$M_R = k1 \times Pa\ (\theta / Pa)^{k2}\ (\tau_{oct} / Pa)^{k3}$								

Table 39. Summary of second step regression for A-6 soils

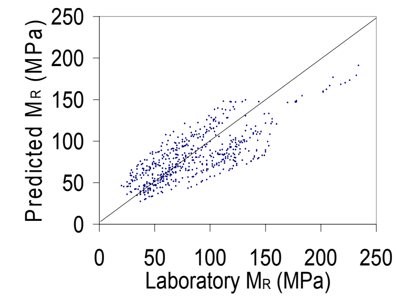
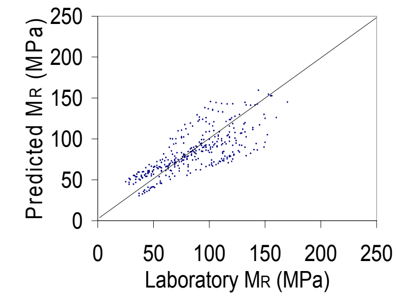
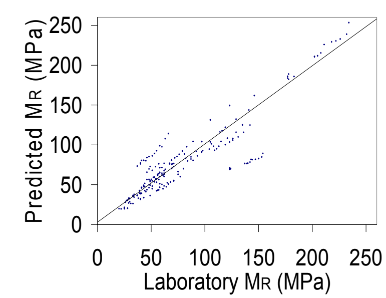
Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-6	MODEL1	All samples	36 (12)	log_k1 = 4.59815 - 0.12918 x MC - 0.00211 x MAXDD + 0.04246 x LL - 0.01500 x CSAND - 0.01746 x CLAY	0.52	0.44	Pr>|t|=0.30 for CSAND	
				k2 = - 2.54229 + 0.00971 x MC + 0.00122 x MAXDD + 0.02703 x SN40 - 0.02122 x SN200 - 0.02393 x FSAND	0.47	0.38	Pr>|t|=0.48 for MC, VIF=18, 31 for SN40, SN200 resp.	
				k3 = 2.08649 - 0.05214 x MC - 0.00071714 x MAXDD + 0.02450 x LL - 0.01231 x S1 + 0.00493 x SN80 - 0.00922 x CLAY	0.49	0.38	Pr>|t|=0.19, 0.22, 0.21 for intercept, MAXDD, S1 resp.	
	MODEL2	Samples compacted near to OMC only	23 (12)	log_k1 = 11.43172 - 0.11840 x MC + 0.07733 x PL + 0.03185 x LL - 0.16290 x S2 + 0.04052 x SN4	0.58	0.45		
				k2 = - 3.39047 - 0.00037458 x MAXDD - 0.01423 x LL + 0.06384 x S2 - 0.01620 x SN4	0.45	0.32	Pr<W=0.0214	
				k3 = 5.70946 - 0.05880 x MC + 0.04341 x PL + 0.01976 x LL - 0.08633 x S2 + 0.02200 x SN4	0.55	0.42	Pr>|t|=0.16 for intercept	
	MODEL3	Samples compacted near to insitu MC only	13 (6)	log_k1 = 17.64679 - 0.00330 x MAXDD - 0.17669 x PL - 0.10358 x S1_2 + 0.04379 x CLAY	0.78	0.66		
				k2 = 0.35299 - 0.03880 x OMC + 0.08025 x PL - 0.04909 x LL + 0.00939 x SN80	0.8	0.71	Pr>|t|=0.20 for intercept	
				k3 = 8.60279 - 0.00107 x DD - 0.06858 x PL - 0.06568 x S3_4 + 0.01672 x SN80 - 0.01271 x SILT	0.68	0.46	VIF=12.3 for SN80	
$M_R = k1 \times Pa\,(\theta / Pa)^{k2}\,(\tau_{oct} / Pa)^{k3}$								

Table 40. Summary of second step regression for A-7-6 soils

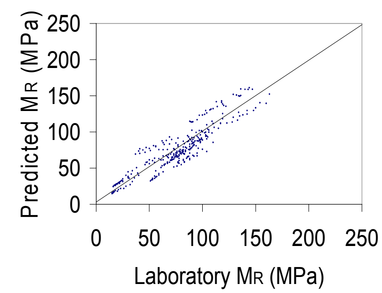
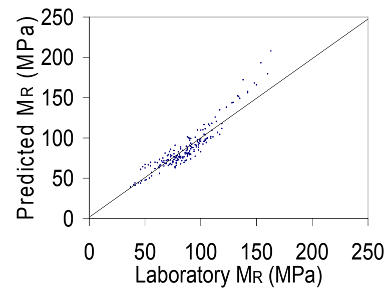
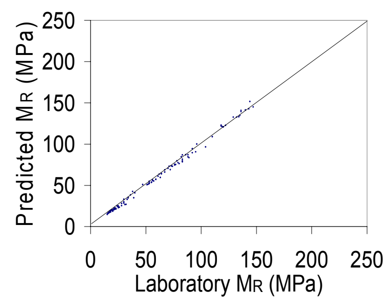
Soil Type	Model No.	Description	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
A-7-6	MODEL1	All samples	20 (9)	log_k1 = 6.54551 - 0.08119 x MC - 0.00202 x MAXDD - 0.00719 x PL - 0.01842 x SN200 - 0.06529 x CSAND	0.79	0.72	Pr>|t|=0.63 for intercept	
				k2 = 9.78523 + 0.00743 x MC - 0.00018782 x DD - 0.01787 x LL - 0.08598 x S1_HALF	0.45	0.3	Pr>|t|=0.21, 0.47 for MC, DD	
				k3 = 3.38876 - 0.03515 x MC - 0.00121 x MAXDD - 0.01073 x PL - 0.00711 x SN200 - 0.02667 x CSAND	0.7	0.6	Pr>|t|=0.19 for PL	
	MODEL2	Samples compacted near to OMC only	13 (7)	log_k1 = 4.52887 + 0.05361 x OMC + 0.00223 x DD - 7.51558 x DDR - 0.01658 x SN4 - 0.01507 x CLAY	0.82	0.7		
				k2 = -1.25242 + 0.01445 x OMC + 0.00092437 x MAXDD - 0.00610 x FSAND - 0.00825 x CLAY	0.8	0.7		
				k3 = 1.12933 + 0.02765 x OMC + 0.00104 x DD - 3.32254 x DDR - 0.00902 x CLAY	0.62	0.43	Pr>|t|=0.26 for intercept	
	MODEL3	Samples compacted near to insitu MC only	8 (6)	log_k1 = 12.86818 - 0.27015 x OMC - 0.00832 x MAXDD + 6.33948 x DDR - 0.06940 x PL + 0.01049 x SN200	0.99	0.99	One sample from Kentucky	
				k2 = 2.66267 - 0.75875 x MCR - 0.00181x DD + 0.00152 x MAXDD + 0.03833 x PL - 0.02020 x SN10	0.99	0.99		
				k3 = - 67.73641 + 0.03590 x MC + 4.17378 x DDR + 0.63629 x S1_HALF - 0.00973 x SN200 - 0.04721 x CSAND	0.99	0.99		
$M_R = k1 \times Pa\ (\theta/Pa)^{k2}\ (\tau_{oct}/Pa)^{k3}$								

Table 41. Summary of second step regression for USCS soil types

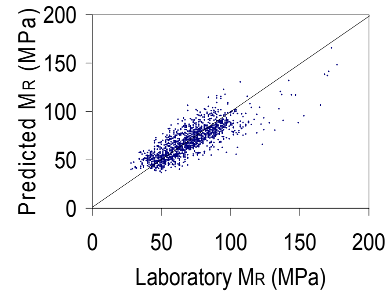
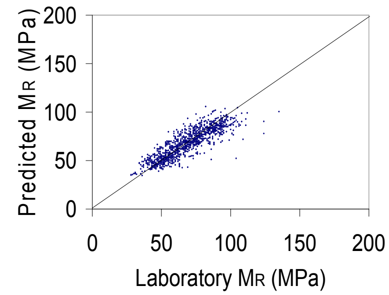
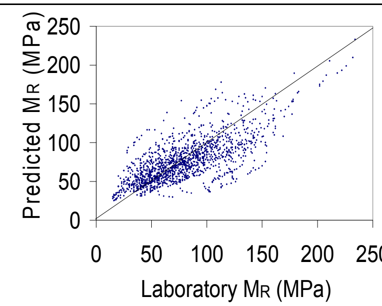
Soil Type	No. of samples (No. of states)	Regression Equation	R^2	Adj. R^2	Comments	Plot
Coarse Grained (All Samples)	91 (19)	logk1 = -1.77341 + 0.00017562xMAXDD + 0.02707xS3 - 0.02043xS1 + 0.00501xS3_8 - 0.00819xSN200 + 0.00501xSILT	0.4	0.36	Pr<W=0.12	
		k2 = -0.49426 + 0.11250xMCR + 0.00026190xDD + 0.00592xS3 - 0.00398xSN40 + 0.00479xFSAND - 0.00006099xCU - 0.0000967xCC	0.45	0.41	Pr>|t|=0.31, 0.29 for intercept & CC	
		k3 = -0.44082 - 0.00232xMC + 0.00021026xMAXDD - 0.00531xS1_2 + 0.00561 xSN10 - 0.00529xSN200	0.63	0.61	Pr>|t|=0.31 for MC, Pr<W=0.085	
Coarse Grained (Samples with CU≤100))	74 (17)	logk1 = 0.61689 - 0.00815xOMC - 0.06144xMCR - 0.80003xDDR - 0.00878xSN200 + 0.00624xSILT + 0.00621xCLAY - 0.00502xCC	0.47	0.41		
		k2 = 0.43372 + 0.00687xMC + 0.00039979xDD - 0.00026666xMAXDD - 0.00331xSN40 + 0.00297xFSAND + 0.00515xCC	0.22	0.15	Pr>|t|=0.27 for intercept	
		k3 = 0.51731 - 0.00390xMC - 0.43830xDDR - 0.00594xS1_2 + 0.00509xSN10 - 0.00070032xSN40 - 0.00418xSN200 + 0.00441xCLAY	0.52	0.47	Pr<W=0.0164	
Fine Grained	97 (16)	logk1 = 6.99969 - 0.11144xOMC - 1.15320xMCR - 0.00154xMAXDD + 0.01875 x PI - 0.02339xS1 + 0.00445xSN200	0.41	0.37		
		k2 = 0.55494 + 0.25904xMCR - 0.00651xPI - 0.00785xSN4 + 0.00712xSN40 - 0.00266xSN200 - 0.00318xCLAY	0.39	0.34	Pr<W<0.0001	
		k3 = 2.08483 - 0.03626xMC - 0.00044337xMAXDD + 0.01104xLL - 0.02024xS1 + 0.00494xSN80 + 0.01012xCSAND + 0.00392xFSAND+0.00287xSILT	0.33	0.27		
$M_R = k1 \times Pa\ (\theta / Pa)^{k2}\ (\tau_{oct} / Pa)^{k3}$						

Table 42. Descriptive statistics for the prediction models

MODEL# *	No. of Samples	No. of M_R data values	Percentage of predicted M_R within ±10 % of laboratory M_R	Percentage of predicted M_R within ± 20 % of laboratory M_R
A-1-b				
MODEL1	29	432	59.95%	94.21%
MODEL2	10	150	96.00%	98.00%
MODEL3	19	282	73.05%	98.94%
A-3				
MODEL1	19	284	63.73%	94.72%
MODEL2	14	209	79.43%	98.56%
MODEL3	4	60	100%	100
A-2-4				
MODEL1	40	600	51.33%	84.33%
MODEL2	28	420	64.29%	89.29%
MODEL3	12	180	85.56%	100%
A-4				
MODEL1	66	988	35.53%	62.15%
MODEL2	41	614	35.83%	66.29%
MODEL3	25	374	39.04%	73.79%
A-6				
MODEL1	36	540	22.59%	42.96%
MODEL2	23	345	33.62%	57.10%
MODEL3	13	195	41.03%	70.26%
A-7-6				
MODEL1	20	300	36.33%	66.33%
MODEL2	13	195	67.18%	95.38%
MODEL3	8**	120	95.83%	100%
Coarse Grained				
All samples	91	1359	50.04%	77.63%
Samples with Cu≤100	74	1109	60.32%	85.75%
Fine Grained	97	1455	30.03%	50.86%

* MODEL1 – Prediction Models developed with all reconstituted samples
MODEL2 – Prediction Models developed with samples compacted at optimum moisture content only
MODEL3 – Prediction Models developed with samples compacted at insitu moisture content only
** One additional sample from Kentucky

Table 43. Descriptive statistics for the validation of prediction models

MODEL# *	No. of Samples	No. of M_R data values	Percentage of predicted M_R within ±10 % of laboratory M_R	Percentage of predicted M_R within ± 20 % of laboratory M_R
A-1-b				
MODEL1	3	45	90.00%	100.00%
A-3				
MODEL1	3	45	68.89%	97.78%
MODEL2	3	45	6.67%	17.78%
A-2-4				
MODEL1	1	15	40.00%	86.67%
MODEL2	1	15	20.00%	40.00%
A-4				
MODEL1	6	90	58.89%	87.78%
MODEL2	6	90	64.44%	83.33%
Coarse Grained				
All Samples	7	103	8.73%	32.04%
Samples with Cu≤100	7	103	22.33%	68.93%
Fine Grained	6	90	37.78%	54.44%

* MODEL1 – Prediction Models developed with all reconstituted samples
MODEL2 – Prediction Models developed with samples compacted at optimum moisture content only

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APPENDICES

All appendices pertaining to this report are provided in the attached CD ROM. There are total of 9 appendices (Appendix A through Appendix I) which constitute 941 pages.