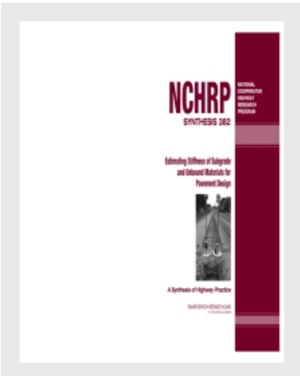

Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP **SYNTHESIS 382**

Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design

A Synthesis of Highway Practice

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The University of Texas at Arlington

SUBJECT AREAS
Soils, Geology, and Foundations

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2008
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Cover: LWD devices in field operation (White et al. 2007).

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Officer
Transportation Research Board

The new Mechanistic Empirical Pavement Design Guide (MEPDG) and other existing pavement design guides use resilient modulus (MR) as the primary input parameter when characterizing stiffness of subsoils and unbound bases. Resilient modulus of soils is typically determined either by using laboratory tests or field tests. This report was prepared to describe the significance of the resilient modulus property, various methods of determining this property of subsoils and unbound bases, and the application of this parameter in the mechanistic empirical pavement design guide. The report will be of interest to design, geotechnical and materials engineers and technicians.

Information collected in this synthesis was based on a comprehensive literature review, surveys of pavement design, materials and geotechnical engineers from state DOTs, and selected interviews. Information collected also included research reports from studies conducted by several state DOTs.

The consultant, Anand J. Puppala, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

ESTIMATING STIFFNESS OF SUBGRADE AND UNBOUND MATERIALS FOR PAVEMENT DESIGN

SUMMARY

The new *Mechanistic Empirical Pavement Design Guide* developed under NCHRP Project 1-37A, and other existing pavement design guides including the 1993 AASHTO flexible pavement design guide use Resilient Modulus (M_R) as the primary input parameter when characterizing subgrade and unbound bases. Resilient modulus of soils is typically determined either by using different types of laboratory tests or using different methods of in situ nondestructive or intrusive tests. Many transportation agencies believe that the laboratory resilient modulus testing is complicated and expensive to perform on a routine basis. Currently, different repeated load triaxial test-based resilient modulus test protocols, including AASHTO test procedures T-274, T-292, T-294, and T-307 methods, have been used by various state departments of transportation (DOTs). Constant modifications of the test methods over the years have resulted in a large resilient moduli test database with considerable scatter of moduli for the same soil types.

Backcalculation of stiffness parameters in the field utilizing nondestructive test methods such as Falling Weight Deflectometer has also been followed by a large number of state transportation agencies. These field methods have both advantages and limitations. Advantages include faster interpretation methods and no need for field sampling of subsoils. Limitations include poor agreement between interpreted moduli and corresponding laboratory-measured moduli and lack of consistency in the interpretations made by various backcalculation programs for the same field data.

In several other cases, pavement design engineers either assume resilient moduli values for various soils or use various empirical relationships to estimate stiffness parameters. Several correlations are available that are based on either laboratory or field methods or a combination of both. For more than 30 years, researchers and practitioners have been developing empirical or semi-empirical correlations to predict the design resilient modulus of subgrades and unbound bases. Although a large number of these correlations currently exist, their accuracy and robustness are highly variable and generally unknown to the pavement design engineers.

This synthesis was prepared with an objective to describe the significance of the resilient modulus property, various methods of determining this property of subsoils and unbound bases, and the application of this parameter in the mechanistic empirical pavement design guide. As a part of the synthesis preparation, two surveys with various state DOT individuals associated with Geotechnical/Materials groups and Pavement Design groups were conducted. The intent of these surveys was to learn the state of practice from these groups with respect to resilient modulus property determination of both bases and subgrades from various methods including laboratory and field methods.

In Geotechnical/Materials group survey responses (41 of 50 states), few respondents noted that they determine M_R from various methods, including laboratory and field methods, and they also provided various details with respect to tests followed and M_R correlations used. The overall satisfaction of the respondents regarding the use of M_R for mechanistic pavement design is still low and this is attributed to constant modification of

test procedures, measurement difficulties, and design-related issues. In Pavement group survey responses (40 of 50 states), similar issues are discussed along with the need to develop simple procedures for resilient property determination. Overall, both surveys provided valuable information for developing the syntheses of various methods for resilient property determination.

This synthesis summarized various methods for determining the resilient properties of unbound pavement materials and subgrades along with their advantages and disadvantages. Information on these methods was gathered through a comprehensive literature review, collection of various state DOT research and pavement design reports, papers published in TRB journals and other publications, surveys of engineers from state DOTs and federal agencies, and selected interviews. The collected literature was then grouped and organized into the following five categories:

- Laboratory methods and measured resilient moduli test results of different types of subgrades and unbound pavement materials,
- In situ nonintrusive or nondestructive type test methods to determine resilient properties,
- In situ intrusive or destructive test methods to determine resilient properties,
- Direct correlations that correlate resilient moduli properties with basic soil properties and compaction conditions, and
- Indirect correlations that express model constant parameters (obtained from an analysis of various types of resilient moduli formulations such as two-parameter bulk stress and deviatoric stress models to three- to four-parameter models) as functions of soil properties.

In each method, an attempt was made to summarize salient findings and conclusions obtained from various state DOT investigations across the United States. Also, promising technologies such as light-weight deflectometers and their potential use for determining design moduli are explained. Wherever applicable, the use of in situ methods for subgrade compaction quality assessment through moduli values is addressed. Because this synthesis is aimed at assisting pavement design engineers in evaluating resilient property determination, various useful practices that could provide reliable estimation of moduli are listed. In the case of laboratory testing, repeated load triaxial tests are mentioned, and in the case of field testing, nondestructive Falling Weight Deflectometer tests and intrusive Dynamic Cone Penetration test methods are mentioned for determining moduli of subsoils. Several direct and indirect moduli correlations are mentioned for future usage. Also, research recommendations and directions for better determination of moduli of subgrades and unbound materials are discussed.

CHAPTER ONE

INTRODUCTION

INTRODUCTION AND DEFINITIONS

Historically, flexible pavement design practices were typically based on empirical procedures, which recommend certain base, subbase, and surface layer types and their thicknesses based on the strength of the subgrade. Recommendation of layer types and their dimensions were established based on AASHO road tests performed during the 1950s. The often-used soil strength parameters in this pavement design practice are California Bearing Ratio (or CBR) value, Hveem *R* value, and Soil Support Value (SSV). All these soil parameters are based on the failures of subgrade soil specimens in the laboratory conditions. However, flexible pavements seldom fail owing to subgrade strength failures during their service life (Huang 1993).

Most of the flexible pavements fail owing to either excessive rutting or cracking of pavement layers as a result of fatigue, temperature changes, and/or softening caused by the surface layer cracking (Barksdale 1972; Brown 1974, 1996). Because flexible pavements do not fail as a result of soil strength failure, the 1986 AASHTO interim pavement design guide and subsequently the 1993 AASHTO pavement design guide recommended the use of a soil parameter known as the Resilient Modulus (M_R) to replace strength-based parameters such as CBR and SSV (Brickman 1989; Mohammad et al. 1994; Maher et al. 2000). Several other investigations also refer to this modulus parameter as M_R in their studies.

The resilient modulus is analogous to the elastic modulus used in elastic theories and is defined as a ratio of deviatoric stress to resilient or elastic strain experienced by the material under repeated loading conditions that simulate traffic loading. Figure 1 presents a schematic of the resilient modulus parameter (M_R). Most bases and subgrades are not elastic and they experience permanent deformation under repeated loads (Uzan 2004). However, because loads applied in the laboratory test for resilient modulus are small when compared with ultimate loads at failure and also the result of the application of a large number of cycles of loading that reduces the plastic deformation, the deformation measured during test cycles is considered as completely recoverable or elastic and hence the recovered deformations are used to estimate the resilient modulus or elastic modulus (or simply modulus or stiffness).

Other forms of moduli and their definitions are presented in Figure 2. The initial slope of the "stress–strain" curve is termed as initial tangent modulus (E_{max}), and the secant modulus (E_1) is termed as the slope of the line that joins the origin and a point on the stress–strain curve that represents

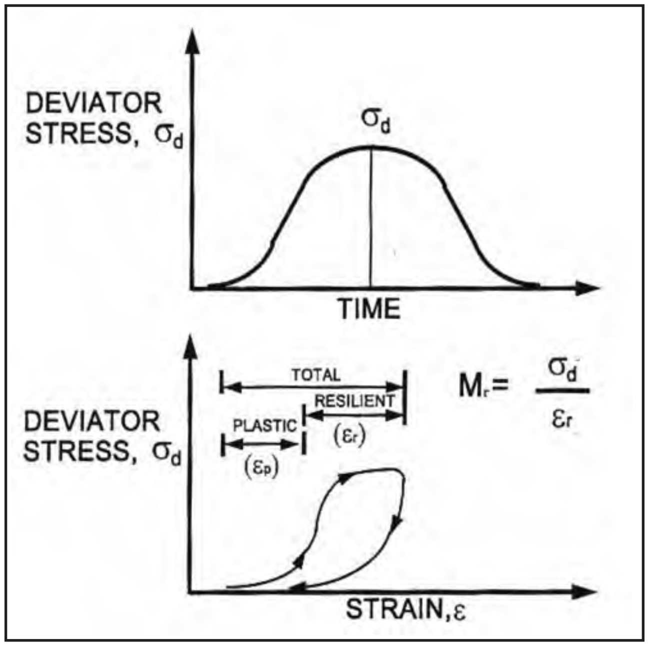


FIGURE 1 Definition of resilient modulus.

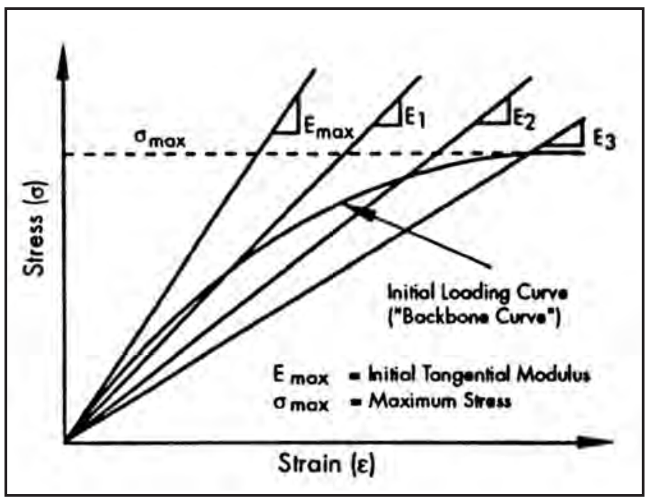


FIGURE 2 Definitions of other elastic moduli parameters (Nazarian et al. 1996).

50% of the ultimate deviatoric stress at which sample fails. The resilient modulus (M_R) parameter is close to E_{max} for stiff materials, and for soft soils the modulus lies in between E_1 and $E_{max.}$ Also, the laboratory methods using repeated load triaxial (RLT) tests measure resilient moduli of tested materials whereas the field nondestructive methods using backcalculation subroutines and other approaches provide the elastic moduli of subgrades and bases.

The main reason for using the resilient modulus or modulus or stiffness as the parameter for subgrades and bases is that it represents a basic material property and can be used in the mechanistic analyses for predicting different distresses such as rutting and roughness. This parameter has been used to directly determine the structural capacity of the subgrade or determine the structural coefficient of the untreated base and subbase layer. Based on the structural number value, pavement layers and their dimensions are designed in the AASHTO pavement design guide.

The pavement design approach is termed as mechanistic because the design is based on the mechanics of materials that relate traffic characteristics and information to pavement response output parameters, such as stress or strain of materials. Pavement response parameters are used to estimate or predict distress using laboratory- and field-measured moduli values. For example, the estimation of vertical compressive strains of subgrade and the moduli properties can be used to understand plastic deformation of subsoil, which contributes to the overall rutting of the pavement system. Such design approach is considered as mechanistic empirical because statistical empirical relationships are used to correlate pavement response parameters and distress magnitudes.

Subsequent pavement design guides, including the 1993 AASHTO *Pavement Design* Guide and the current *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*), describe design methodologies that use resilient modulus as the primary input parameter for characterizing subgrade, subbase, and base materials. Resilient modulus values of these materials are typically determined by performing laboratory tests using RLT tests simulating traffic loading conditions. Different resilient modulus test protocols, including AASHTO test methods T-292, T-294, and T-307 as well as TP-46, have been used by the departments of transportation (DOTs) in the laboratory conditions. All these test procedures have certain differences with respect to test sequences of applying confining and deviatoric stresses, measurement of deformations either inside the triaxial cell or outside the triaxial cell, application of seating stresses, specimen preparation steps, and conditioning methodology applied before the actual testing. These differences do contribute to several uncertainties, which are explained in chapter three. Table 1 presents a chronology of how these test methods were developed in the estimation of resilient moduli of subgrades.

Also, a CD-ROM guide developed by the FHWA as a part of Long-Term Pavement Products (LTPP) presents several interactive tutorials on resilient modulus of unbound materials. Three videos that depict the M_R test procedures were developed to aid practitioners, laboratory managers, and technicians (FHWA 2006).

Irwin (1995) presented various limitations in both current test methods with respect to applied confining and deviatoric pressures and current nonlinear regression models

TABLE 1
CHRONOLOGY OF AASHTO TEST PROCEDURES FOR M_R MEASUREMENTS

Test Procedure	Details
AASHTO T-274-1982	Earliest AASHTO test procedure; No details on the sensitivities of displacement measurement devices were given; Criticisms on test procedure, test duration (5 hours long test) and probable failures of soil sample during conditioning phase; testing stresses are too severe.
AASHTO T-292-1991	AASHTO procedure introduced in 1991; Internal measurement systems are recommended; Testing sequence is criticized owing to the possibility of stiffening effects of cohesive soils.
AASHTO T-294-1992	AASHTO modified the T-292 procedure with different sets of confining and deviatoric stresses and their sequence; Internal measurement system is followed; 2-parameter regression models (bulk stress for granular and deviatoric stress model for cohesive soils) to analyze test results; Criticism on the analyses models.
Strategic Highway Research Program P-46-1996	Procedural steps of P-46 are similar to T-294 procedure of 1992; External measurement system was allowed for displacement measurement; Soil specimen preparation methods are different from those used in T-292.
AASHTO T-307-1999	T-307-1999 was evolved from P-46 procedure; recommends the use of external displacement measurement system. Different procedures are followed for both cohesive and granular soil specimen preparation.
NCHRP 1-28 A: Harmonized Method-2004 (RRD 285)	This recent method recommends a different set of stresses for testing. Also, a new 3-parameter model is recommended for analyzing the resilient properties. The use of internal measurement system is recommended in this method.

used to analyze the resilient moduli data of subgrades and bases. Irwin (1995) also noted the need for semi-log models that capture nonlinear subgrade material behavior under traffic loading and can provide moduli when tensile stresses are encountered in the subgrades or at the pavement layer interfaces. Other methods of determining subgrade and base layer moduli or stiffness properties deal with backcalculation of the moduli in the field using nondestructive tests such as Falling Weight Deflectometer (FWD). This approach has been used by several agencies and used in both pavement design and rehabilitation design tasks.

In *MEPDG*, for pavement design, material and geotechnical engineers can provide three types of resilient moduli or stiffness input for both unbound bases and subgrades. The first one is referred to as Level 1 input and it requires the determination of moduli of the materials from laboratory or field tests. The second one is known as Level 2 in which users determine resilient moduli values from various empirical relationships developed locally or elsewhere to estimate the resilient properties of soils. The last type is referred to as Level 3 in which users assume resilient modulus values based on threshold default values for different soil types.

For more than 30 years, researchers have been developing and revising procedures to measure resilient modulus of subgrades and unbound bases either by performing tests on specimens in the laboratory or using a nondestructive test in the field or using empirical or semi-empirical relationships between moduli and material parameters. Although a large number of correlations currently exist, their accuracy and robustness are still unknown to the pavement designers who routinely use them.

SYNTHESIS OBJECTIVES AND OVERVIEW

This synthesis was initiated to summarize various resilient modulus test procedures using direct and indirect methods for either measuring or interpreting the resilient properties of unbound pavement materials and subgrades.

In direct test measurements, testing procedures currently reported in the literature are covered; in indirect test methods, laboratory-based stiffness measurements using geophysical methods, in situ intrusive tests such as the dynamic cone penetration (DCP) and cone penetration tests (CPTs), and backcalculation approaches utilizing nondestructive tests were summarized and discussed. In each method, both advantages and disadvantages are mentioned. This section is followed by a comprehensive summary of various predictive correlations for resilient modulus property of subgrades and unbound bases.

Both laboratory and field methods as well as correlations are then summarized with respect to their application for pavement design. Reliability of the test procedure, repeatability, and limitations as well as new research directions in these methods are also presented. Hence, this synthesis is aimed at assisting pavement design engineers in evaluating direct resilient property measurements against empirical correlations-based resilient moduli predictions. The recommended practices that could provide high-quality predictions using the available empirical correlations are also included in the synthesis.

Information collected in this synthesis was based on a comprehensive literature review, surveys of pavement design and materials/geotechnical engineers from state DOTs, and selected interviews. Information collected here included various research reports prepared on resilient moduli studies conducted by several DOTs.

OUTLINE OF CHAPTERS

This synthesis contains six chapters. Chapter two presents a survey description, survey respondents' information, survey results, and summary statistics. This information is included in chapter two before other chapters primarily to give a picture about how the DOT engineers perceive the current test procedures, correlations, and field methods for the determination of resilient properties of subgrades and unbound bases.

Chapters three and four describe laboratory and field test methodologies and chapter five presents correlations currently provided in the literature for the determination of the resilient properties. This is followed by a comprehensive summary discussion that enlists various DOTs and the test practices they followed to determine resilient properties. Similar discussion is made with respect to field test methods of both nondestructive and destructive or intrusive methods. For correlations, both direct and indirect correlations currently used or recommended by various DOTs are listed in this chapter. Both advantages and limitations of these practices are included in this chapter.

Chapter six presents findings from the literature information compiled in chapters three, four, and five, and summarizes the "useful practices" for better determination of resilient properties of unbound bases and subgrades. This chapter provides a summary of the key findings and opportunities for additional research needs.

CHAPTER TWO

SUMMARY OF SURVEY RESPONSES

INTRODUCTION

This chapter details the survey approach followed for this synthesis in gathering various details and specific information regarding the resilient properties of subgrades and unbound bases among state DOTs. The survey had two components: one component was prepared for materials/geotechnical engineers and the other one was prepared for pavement design engineers.

Test procedures followed, and test details (including the number of samples per test and other information), constitutive model expression, empirical and semi-empirical expressions for resilient properties, and field test methods for determining resilient properties are queried in the surveys prepared for materials/geotechnical engineers. Pavement design details, structural support of unbound bases, and subgrades were included in the surveys prepared for pavement design engineers. All the survey results collected from the state DOTs are summarized in this chapter.

SURVEY QUESTIONNAIRE

One of the main objectives of Synthesis Topic 38-09 was to gather information about how various agencies determine resilient moduli of subgrades and unbound bases and how these properties have been used in the design of pavement systems. To accomplish this objective, the survey questionnaire was designed in three parts. Part I requests information from the survey respondents about their affiliation agencies. Part II of the survey was to be completed by the state materials/geotechnical engineer or agency official most knowledgeable about material testing practices, and Part III was to be completed by the pavement design engineer or agency official most knowledgeable about pavement design practices. The entire survey questionnaire is presented in Appendix A.

SURVEY PROCEDURE STEPS

The following steps were followed for conducting the survey. A 40-question electronic survey containing primarily multiple-choice-type questions was used for Part II on a Web-based platform. The Web-based program is a professional software program that is used to host surveys and gather input for the surveys from various entities. The program then analyzes the gathered results in a professional format using bar charts and pie charts. The unique link for each state survey was created and e-mailed to materials/geotechnical engineers from all 50 state DOTs. Each respondent received a special coding to start providing responses to survey questions.

Based on the responses, a few respondents were contacted for additional questions or a brief interview to review certain responses. These interviews were conducted to clarify any discrepancies found in the questionnaire or to obtain additional information. Agencies that did not respond within four weeks were contacted by the software company. For pavement design surveys, another set of surveys was mailed to pavement design engineers for each DOT.

In certain cases, the initial state contacts from a few state DOTs were not responsive to the survey; some were no longer at their jobs owing to promotions or retirement, some left the agency, and some failed to respond for other reasons. In those cases, alternate representatives were sought and survey e-mails were sent. In all cases, another person from the DOT was selected to complete the survey. Appendix B presents the details of individuals from various DOTs reached for these surveys.

Data were either taken from the software program or entered into Microsoft Excel for preparing illustrations of the survey response results. The majority of these results are presented in Appendix C. A few salient questions are included in this chapter for explanations.

SURVEY RESULTS

Geotechnical/Materials Survey Results

The survey was transmitted to 50 state DOTs, and a total of 41 responses (82%) were received. In the survey analysis presented here, the total number of responses (N) used is 41. Salient details of the surveys are presented in this chapter; the rest of the details are provided in Appendix C.

The responses from state DOTs with respect to design projects in which resilient moduli of subgrades and bases were used are summarized in Figure 3. Twenty-two DOTs

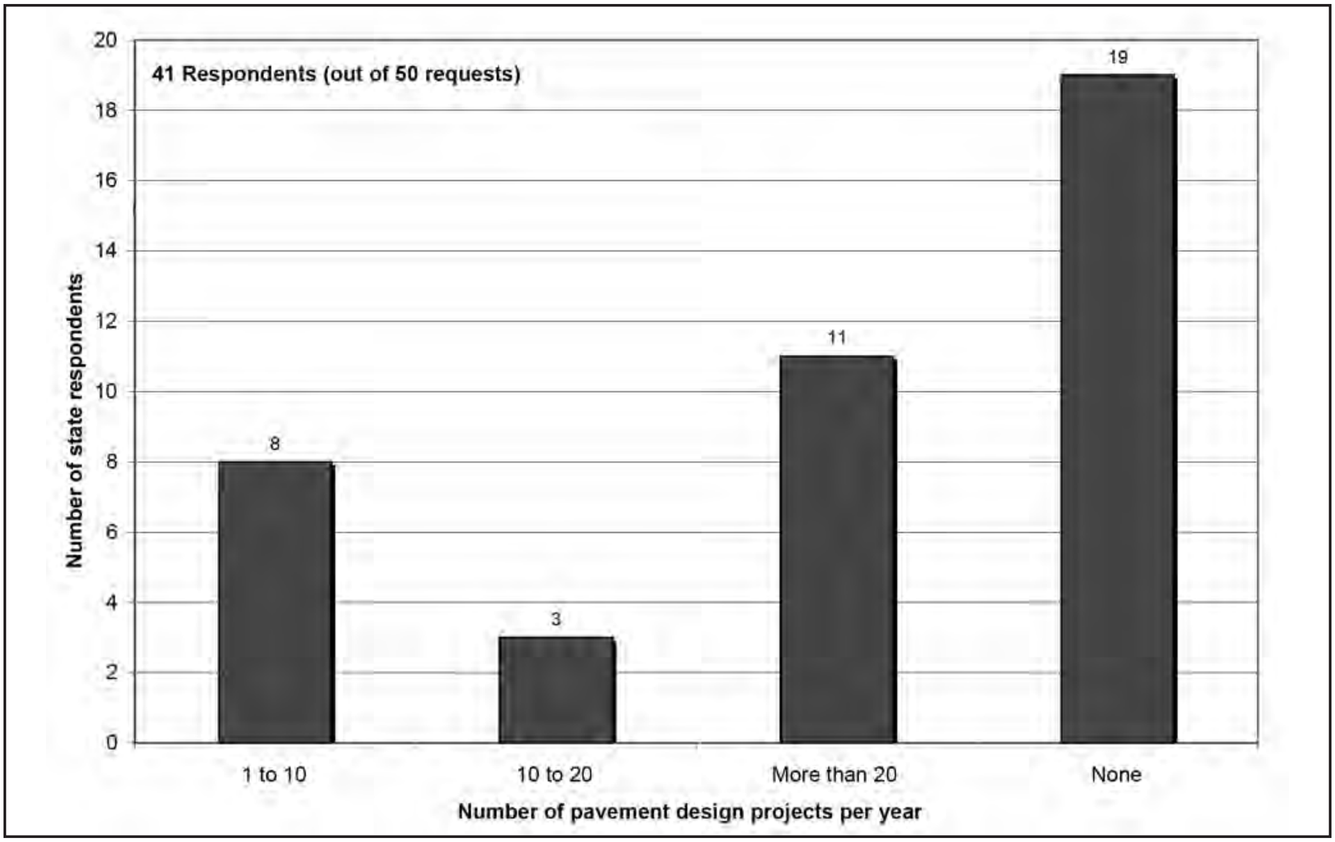


FIGURE 3 Number of DOTs that responded favorably for measurement of resilient moduli properties of subgrade/unbound bases.

responded that they do use resilient modulus tests in routine pavement design and 19 noted that they do not measure the resilient moduli properties of subgrades and unbound bases. Among the 22 respondents, 11 stated that they perform resilient modulus tests in more than 20 pavement projects annually.

Figures 4*a* and 4*b* present the number of respondents that dealt with different types of soils and unbounded bases, respectively. The respondents are asked to choose more than one type of soil/unbound base material. Hence, the overall numbers do not add up to the total number of respondents. The majority of state DOTs mentioned that they encountered silty clay subgrade (28 of 41 respondents) in their pavement projects and used crushed stone aggregates (22 of 41 respondents) in pavement base layers.

Responses Related to Laboratory Measurements

With respect to M_R measurements, 12 of the 41 respondents noted that they *do* use laboratory methods to determine resilient moduli properties. Among these 12, eight respondents noted that geotechnical/materials laboratories were responsible for performing resilient modulus tests. Four respondents noted that they use either outside laboratories or a university laboratory to perform these tests.

Seven respondents noted that they follow specific guidelines regarding the number of tests to be performed per volume of the subgrade or length of the highway. Three respondents mentioned the same for unbound bases. Details of these guidelines included one test per mile of roadway, one test per project per new pavement, and tests on soil samples when the soil types varied along the length of the pavement.

Nine respondents have used RLT tests to measure resilient moduli of soil samples. In the RLT tests, four followed AASHTO T-307 procedure, and two followed the NCHRP 1-28 A Harmonized procedure. The remaining respondents followed T-294, TP-46, or modified resilient modulus test methods to determine the M_R of subgrades and bases.

With respect to test procedure details, eight respondents prepare laboratory-fabricated specimens for new pavement projects and four use similar specimens for rehabilitated pavement design. Four respondents noted that they used undisturbed field specimens for pavement rehabilitation work (see Figure 5). The total numbers of responses is different, because a few of the respondents who did not respond to the earlier question on laboratory measurements replied to this question and a few other respondents selected more than one choice.

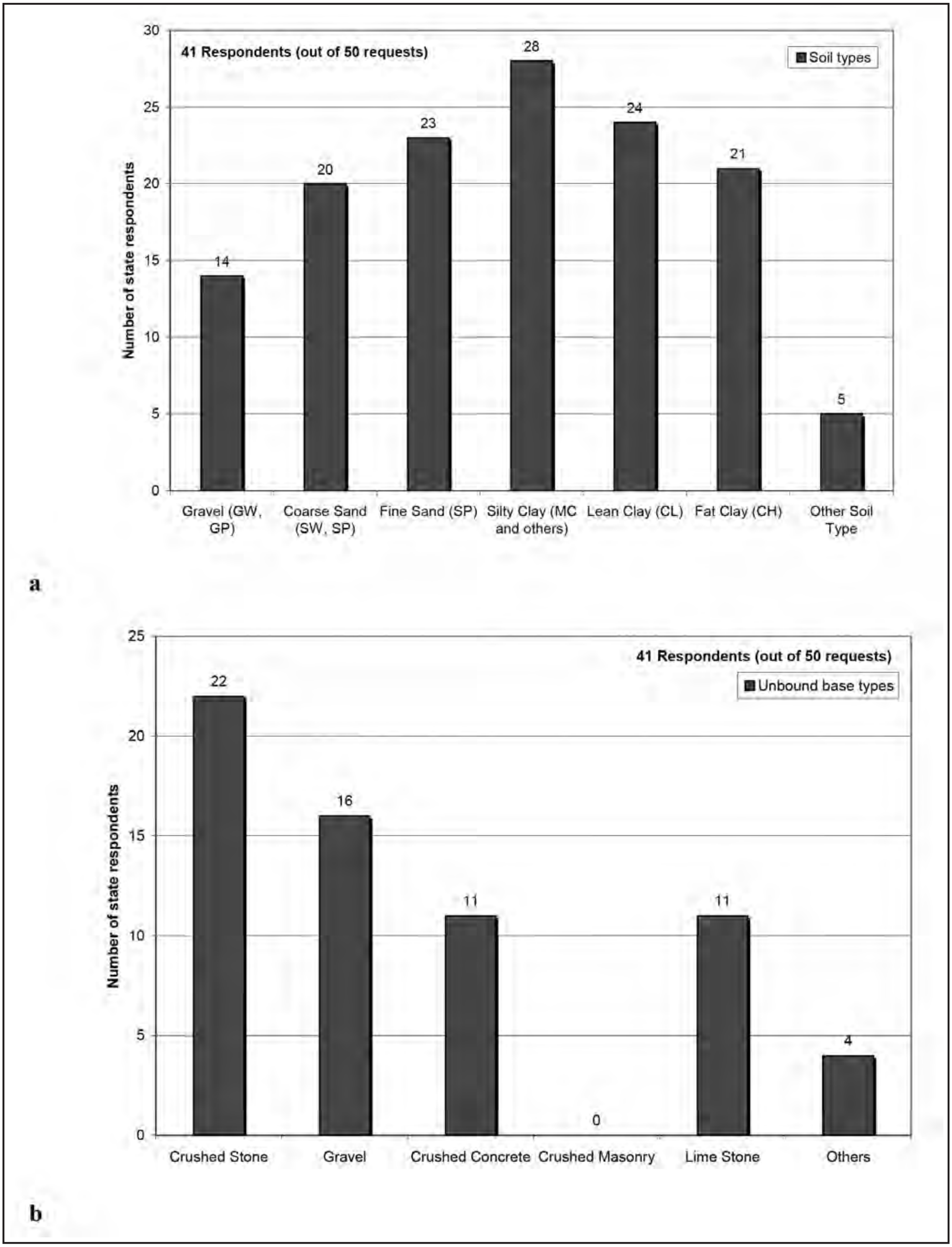


FIGURE 4 Types of subgrades encountered and unbound base material used in pavement systems by different state DOTs: (a) subgrade; (b) unbound bases.

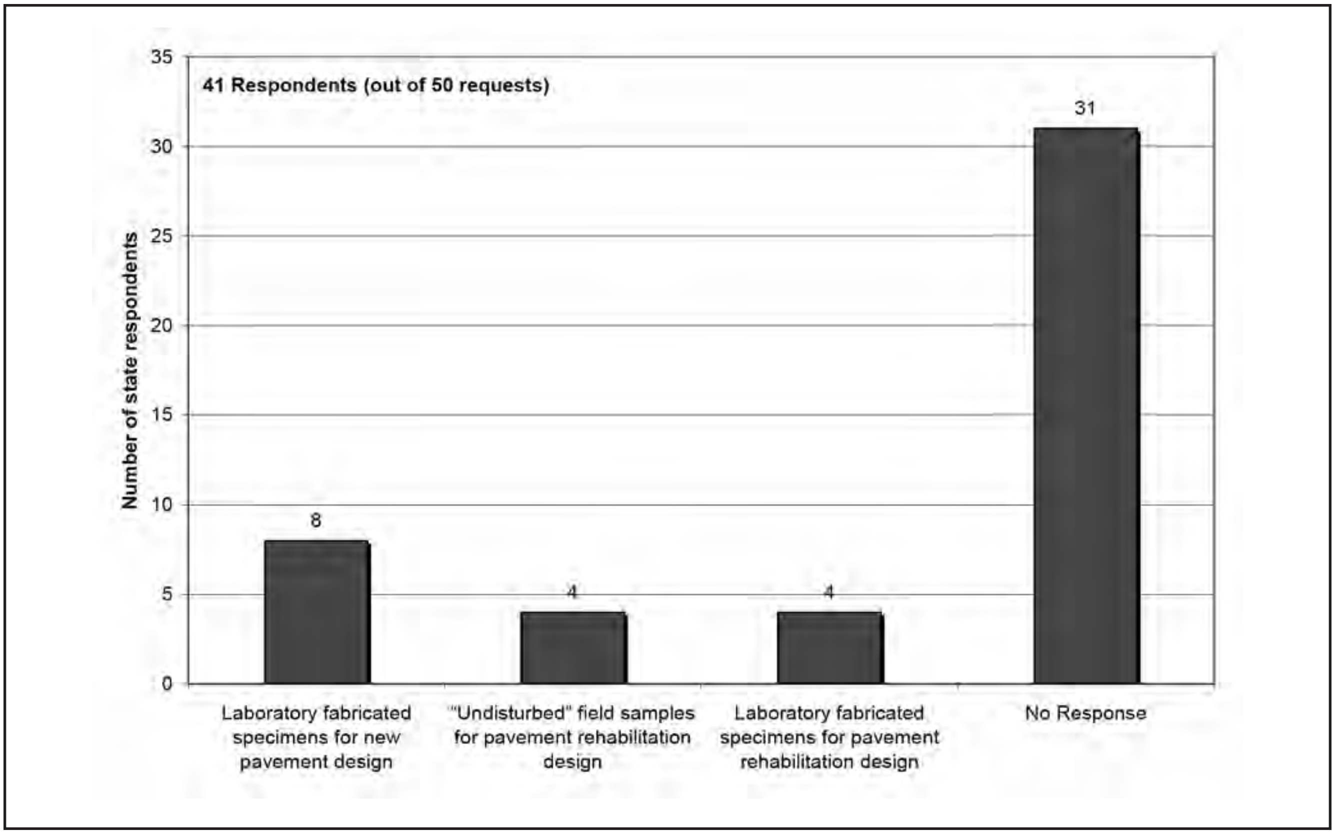


FIGURE 5 Details on the laboratory specimens used in resilient moduli tests.

Figure 6 presents survey responses related to specimen preparation procedures followed for laboratory testing for both subgrades and bases. For subgrades, the numbers responded favorably for impact compaction, static compaction, kneading compaction, and vibratory compaction methods (4, 3, 2, and 2, respectively) and favorably as well for bases (1, 1, 0, and 4, respectively).

With respect to moisture conditioning of the soil specimens in resilient modulus testing, four respondents noted that they consider moisture conditioning of specimens before resilient modulus testing. Moisture conditioning was not specified in the standard test procedures for the measurement of resilient properties. With respect to the number of tests per soil type, two respondents noted that they perform three tests for each subgrade type. Four others reported that the number of tests per soil type varies and depends on their engineering judgment.

Regarding the selection of laboratory moduli for pavement design, one respondent noted using a regression model with field confining pressure and deviatoric stresses to determine the design moduli for both bases and subgrades. Another respondent applied confining and deviatoric stresses simulating field conditions in laboratory testing. Five respondents include the lowest moduli measured in the laboratory to taking an 85th percentile value from the saturated specimen test results.

Figure 7 summarizes the responses with respect to problems experienced in the laboratory M_R testing. Most of the respondents (six) noted that they are unsure whether the test method provides true modulus of subgrades for pavement design and rehabilitation. With respect to advantages of laboratory testing, four respondents indicated that the laboratory resilient modulus tests are better test methods, whereas two respondents reported that the laboratory tests are better indicators of field performance.

Field $\mathrm{M_R}$ *Measurements and FWD Studies*

Twenty-five of the 41 respondents stated that their agency performs field tests to determine the resilient moduli properties of soils. Twenty-four respondents noted that they use FWD tests to determine resilient modulus of subgrade and unbound bases, whereas three respondents mentioned the Dynaflect method and one respondent noted the GeoGauge method. In the case of other responses (three), a respondent from Maine noted the use of a Portable Seismic Pavement Analyzer method for their projects.

Twenty respondents noted that the main intent in performing field FWD tests is to determine subgrade moduli for pavement rehabilitation. Twelve respondents indicated that FWD tests are useful in determining structural coefficients of pavement layers. Three respondents reported that the FWD test is used to ensure that laboratory moduli are

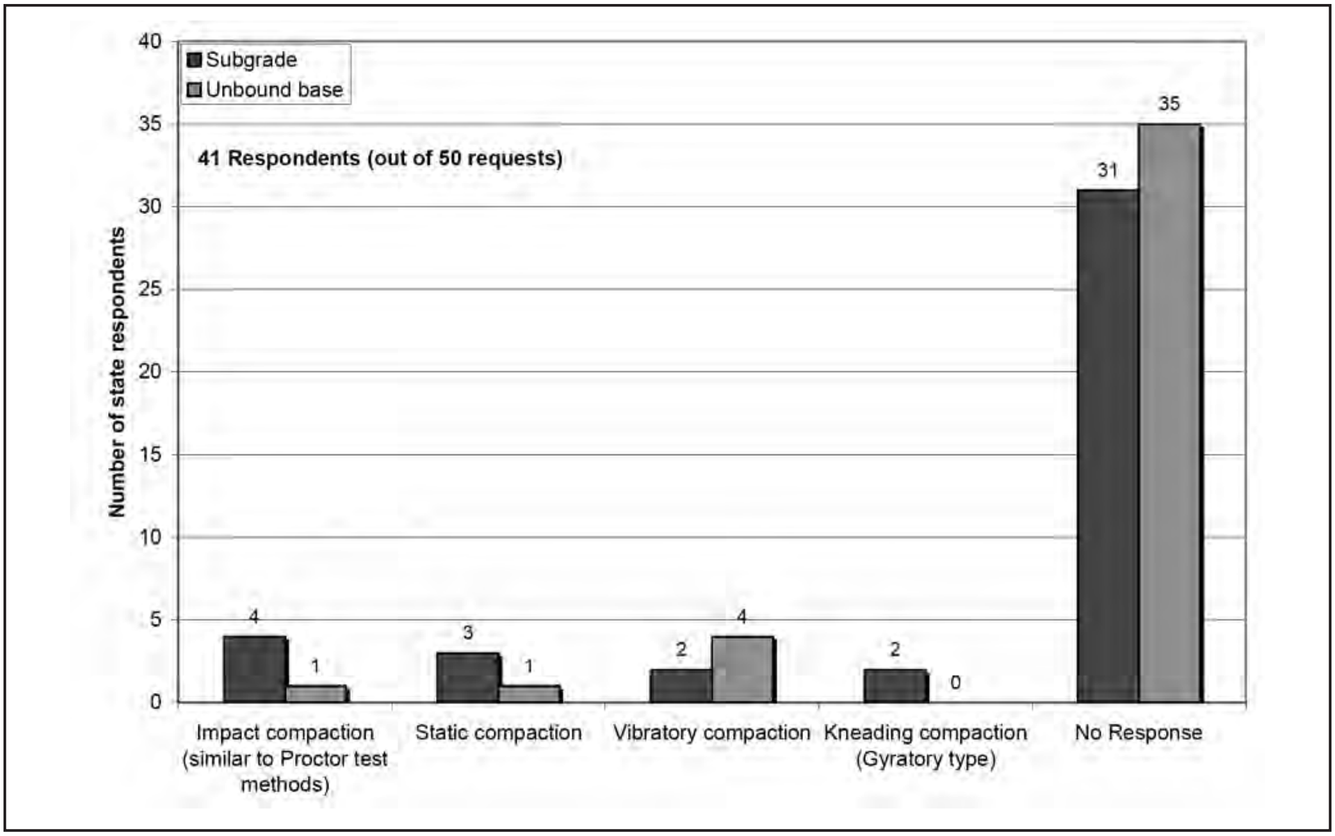


FIGURE 6 Laboratory compaction procedures followed in soil specimen preparation.

representative of field moduli. Eleven respondents noted that they follow specific guidelines regarding the number of FWD tests. Some of the guidelines are reported as FWD tests conducted at 50 ft (15 m) intervals for urban roads and 200 ft (60 m) intervals for rural roads, and 810 ft (250 m) intervals for the network level to 310 ft (100 m) for the project level. Others mentioned the use of 9,000 lb of load to drop on a pavement section several times.

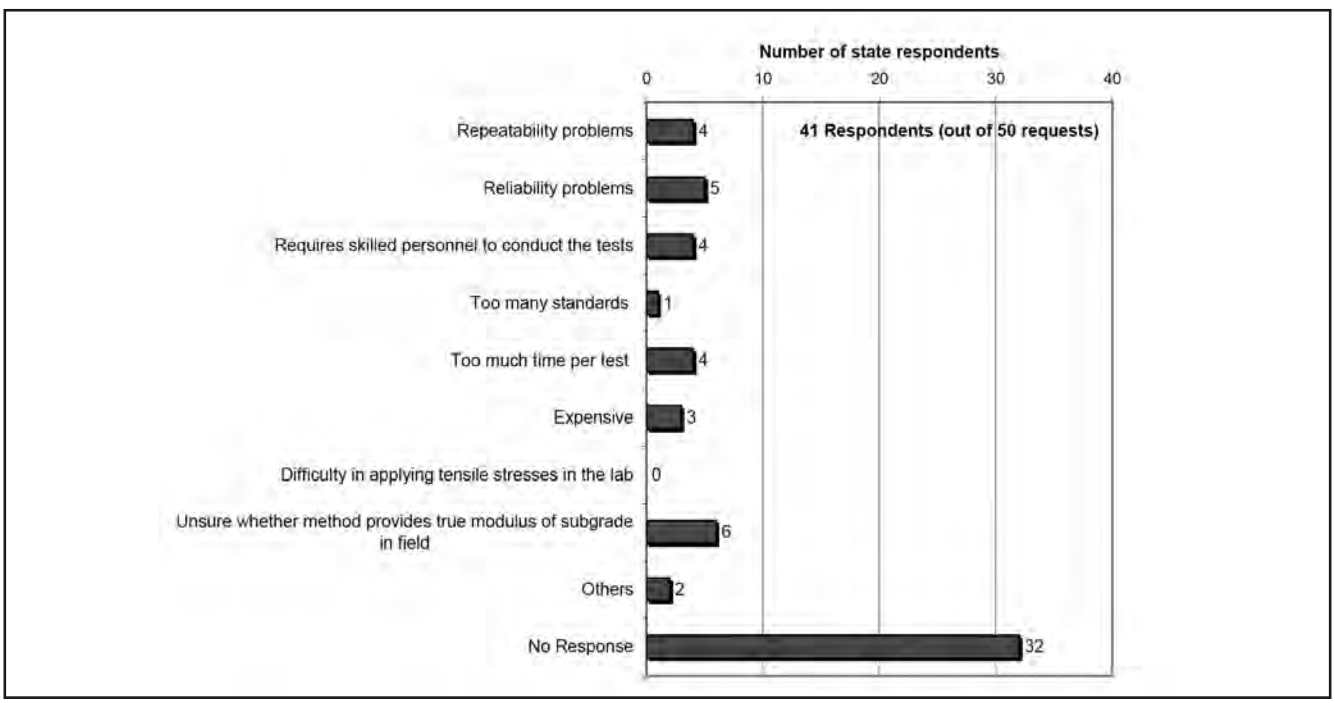


FIGURE 7 Problems related to laboratory resilient modulus tests.

Figures 8 and 9 present survey responses regarding the limitations of FWD methods for subgrades and bases, respectively. Respondents were asked to list their top three responses to this question. Most respondents (five) mentioned that there is no correlation among the laboratory-determined moduli and that different backcalculation software provided different moduli.

With respect to advantages, the majority of the respondents (18) noted that the FWD tests are faster test methods. Fourteen respondents indicated that this method is inexpensive (see Figure 10). Because the respondents were asked to select more than one choice, the total number of responses is higher than 41. The Maryland State Highway Administration stated that the FWD test was typically performed at

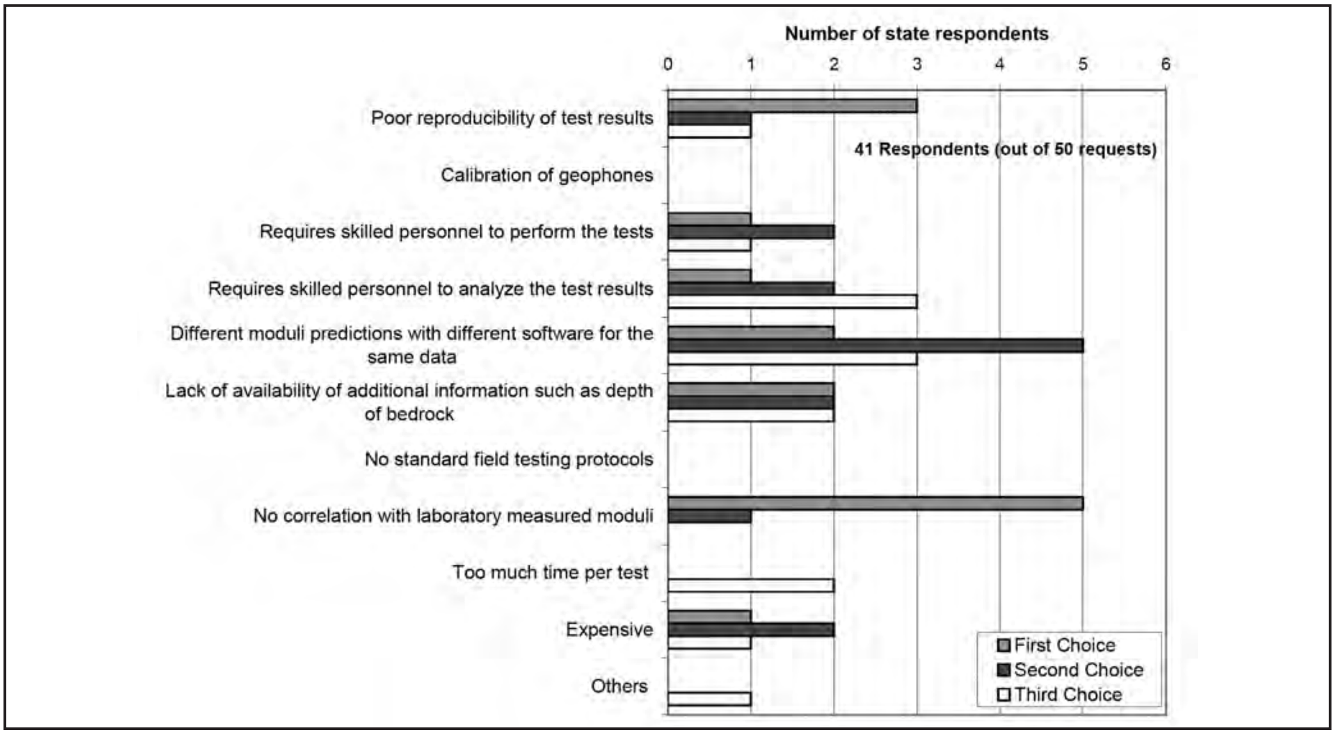


FIGURE 8 Responses on limitations of FWD tests for M_R backcalculation of subgrades.

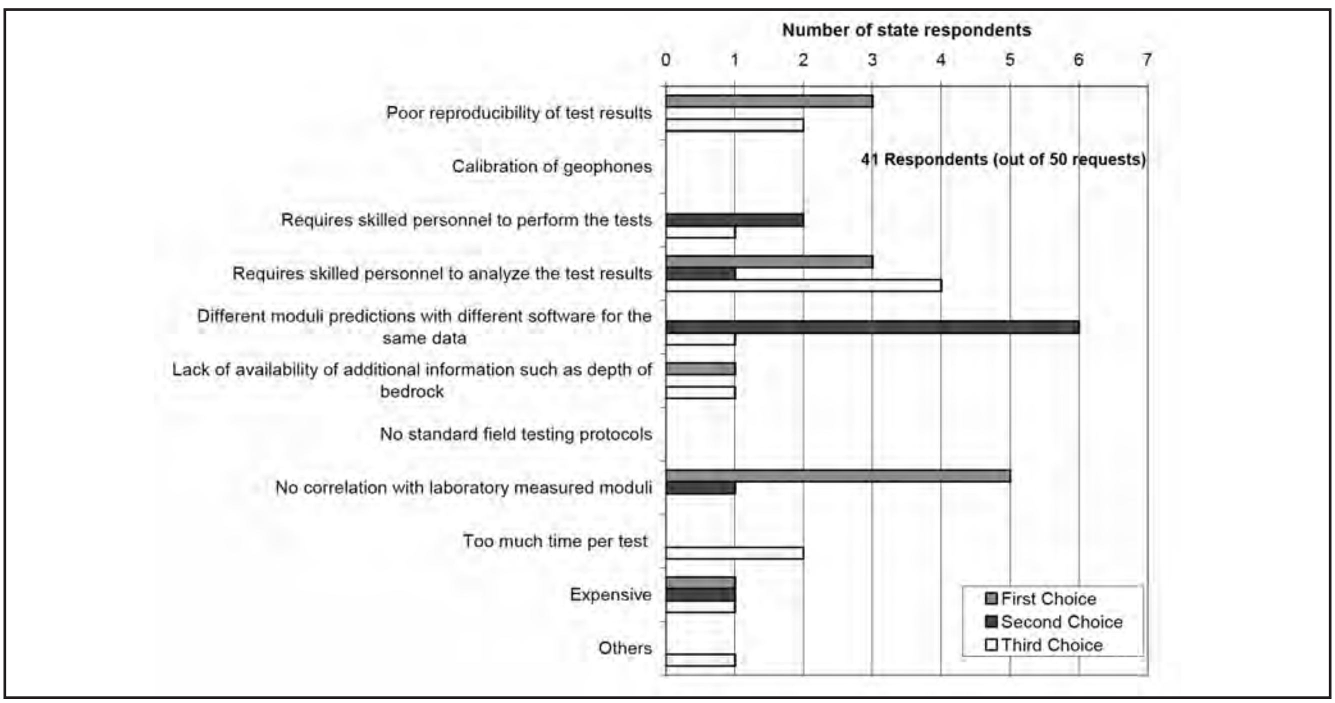


FIGURE 9 Responses on limitations of FWD tests for M_R backcalculation of unbound bases.

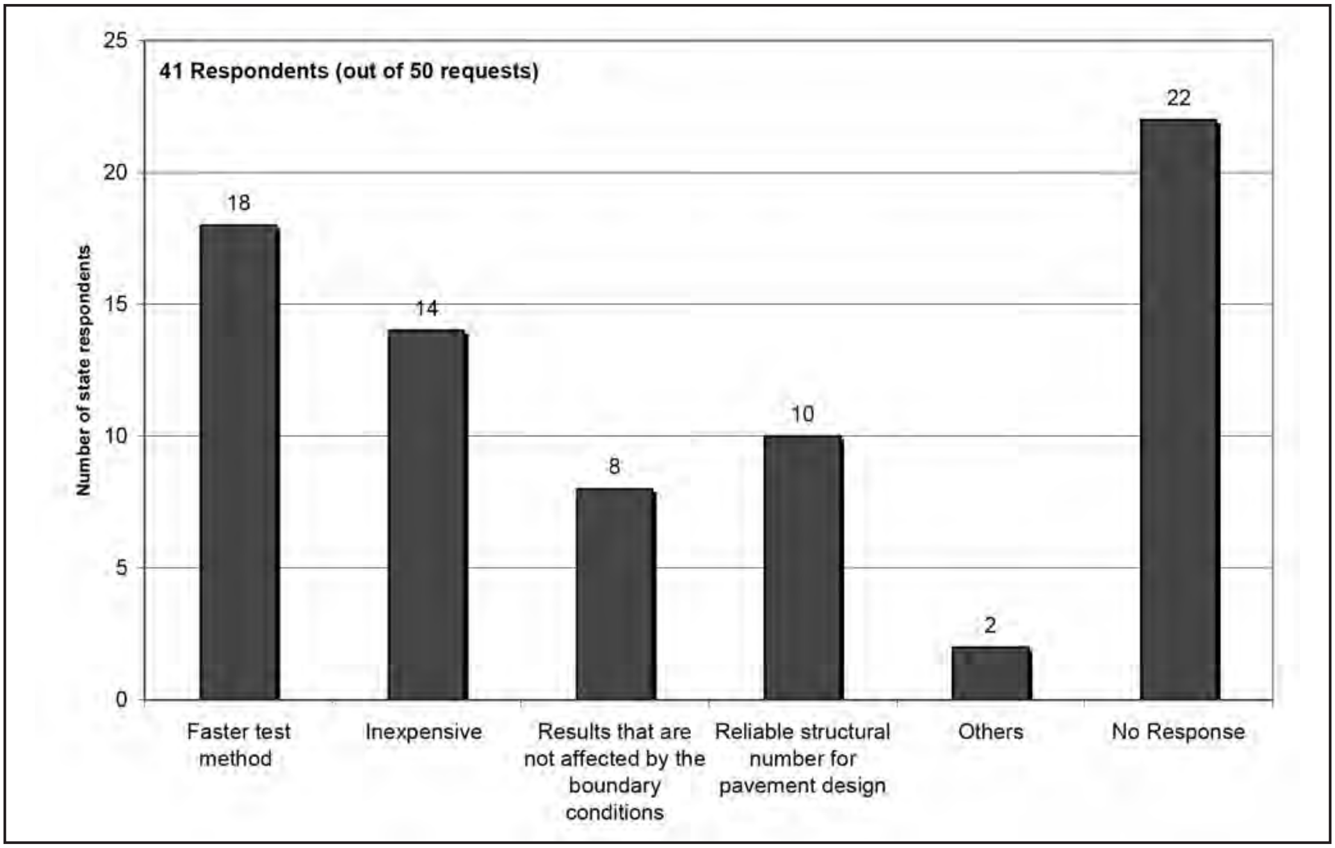


FIGURE 10 Responses on advantages of FWD tests.

many test locations in each project (150 per project). Montana DOT stated that the FWD method would be good when used in conjunction with ground-penetrating radar (GPR). With respect to the use of FWD moduli for pavement design, a few respondents noted that they use 1993 AASHTO design guide recommendations for reducing FWD moduli to determine the resilient modulus value.

Field Tests and Nondestructive Tests Other Than FWD

One respondent stated that the agency uses other nondestructive tests for quality control and quality assurance (QC/QA) studies for indirect compaction quality evaluation for new pavement construction. Another respondent noted that the agency uses these tests to determine subgrade moduli for pavement rehabilitation. Two respondents stated that their agency usually performs or conducts these tests to determine the structural coefficients of pavement layers.

For the overall assessments of other nondestructive methods for subgrades, three respondents noted that these test procedures are well established, whereas one respondent pointed out poor reproducibility problems and the need for more research on analysis routines. From the responses received on other nondestructive methods, more studies are still needed to better understand and validate the methods for M_R estimation.

M_R *Correlations*

Fourteen respondents stated that they use empirical or semi-empirical correlations. Figure 11 presents various responses with respect to the use of correlations. Direct correlations between M_R and other soil properties were used for both subgrades and unbound bases by eight and six of the respondents, respectively (Figure 11). Seven respondents reported that they used correlations that were recommended by the AASHTO design guide and six reported that they use local or their own correlations. Only two respondents used the correlations drawn from the literature.

Figure 12 shows the level of reliability of the correlations per the respondent DOTs. The majority of the agencies (seven for subgrades and eight for unbound bases) characterized the level of reliability of these correlations as fair. Three noted these methods as “very good” to “good.” Additional tests for evaluation are performed by five respondents for subgrades and three respondents for unbound bases. A Kansas DOT respondent stated that they verify the correlation predictions if they have FWD field data. Colorado specified that they perform plasticity index (PI), gradation, density, and moisture tests to cross-check the correlation predictions. The majority did not respond to this question, implying that they do not use correlations for moduli predictions.

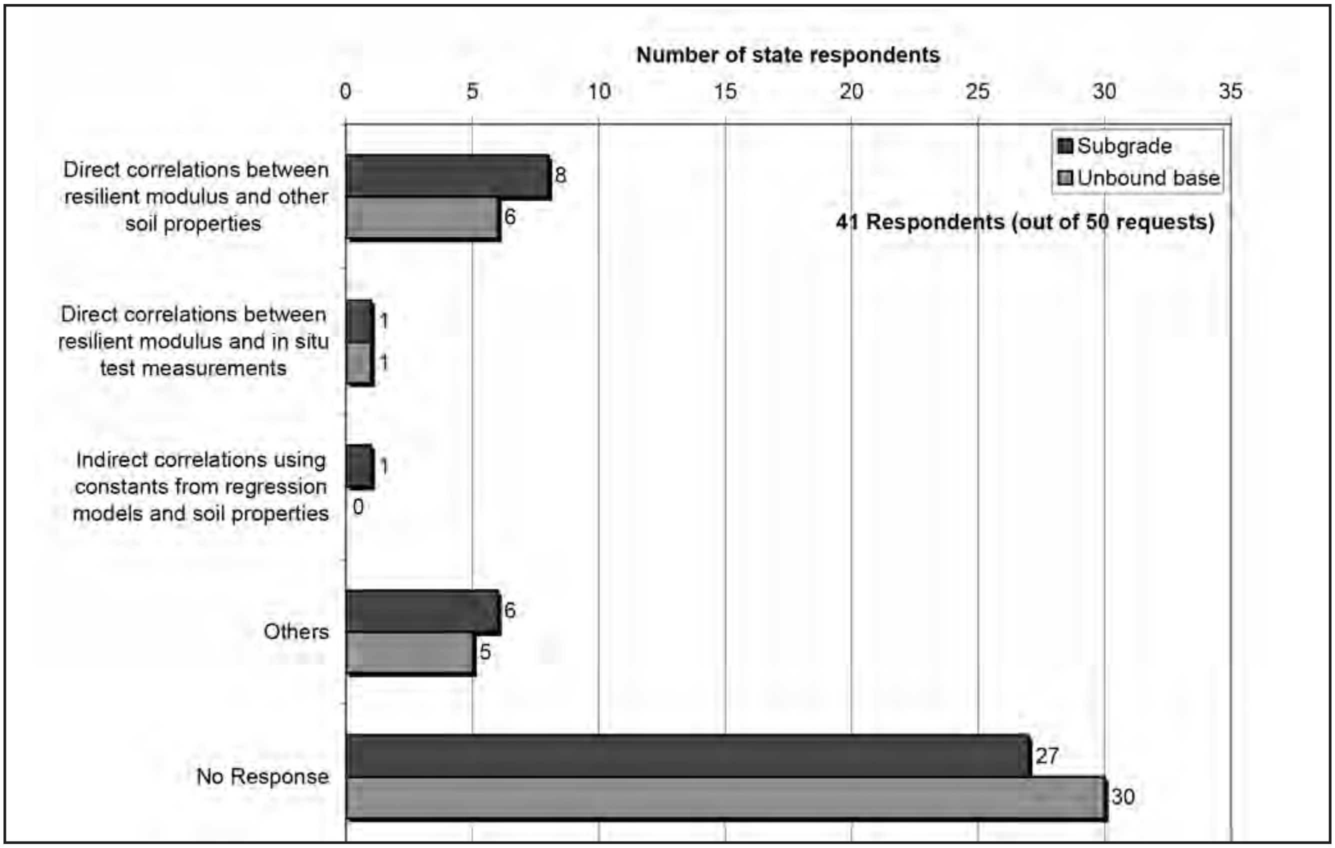


FIGURE 11 Types of correlations used to determine the resilient moduli by state DOTs.

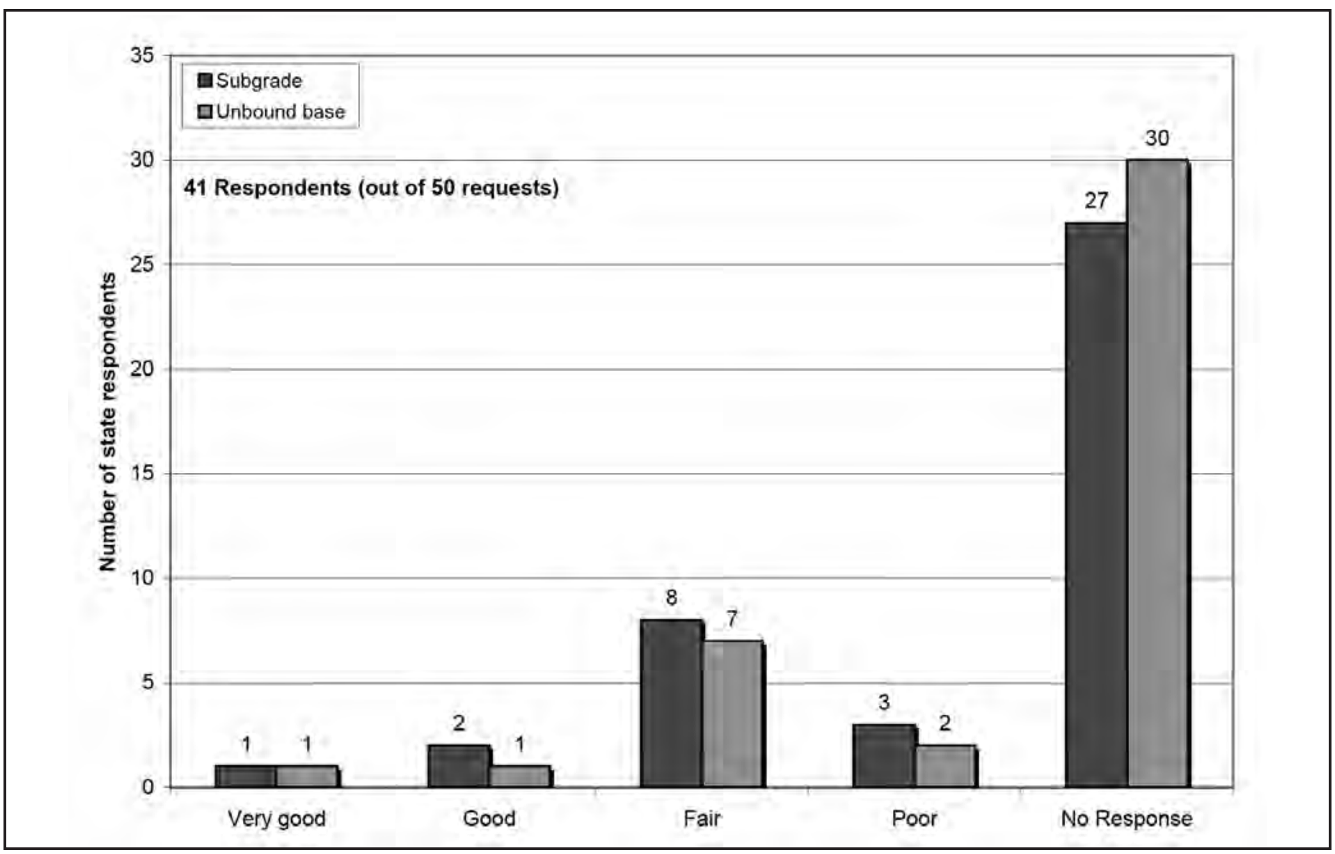


FIGURE 12 Reliability of correlation methods characterized by state DOTs.

Figures 13*a* and 13*b* present the limitations of the correlations as identified by the DOT for subgrades and bases, respectively. The majority of the respondents (10 for subgrades and seven for bases) opined that the correlations were developed from a limited database.

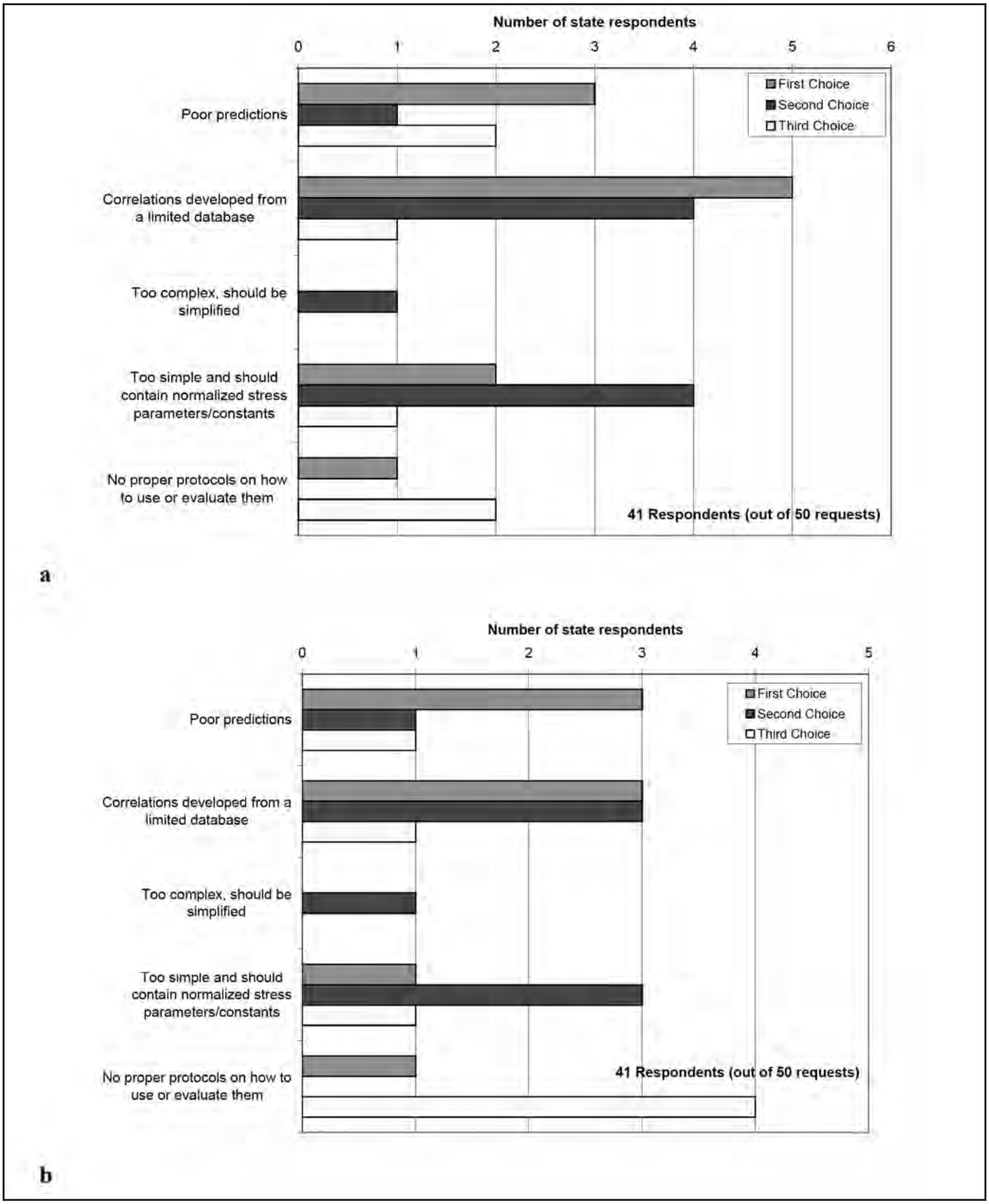


FIGURE 13 Limitations of correlation methods to determine resilient modulus: (a) subgrades; (b) unbound bases.

Final Summary Questions for Geotechnical/Materials Engineer

Sixteen and 11 of the respondents are satisfied with the existing methods to determine resilient moduli properties of subgrades and unbound bases, respectively (see Figure 14). Figure 15 presents reasons for dissatisfaction with the current methods. Overall, the survey response is limited because of the lack of responses. Reasons for no responses are attributed to a lack of familiarity with the M_R, changes in test procedures, length of

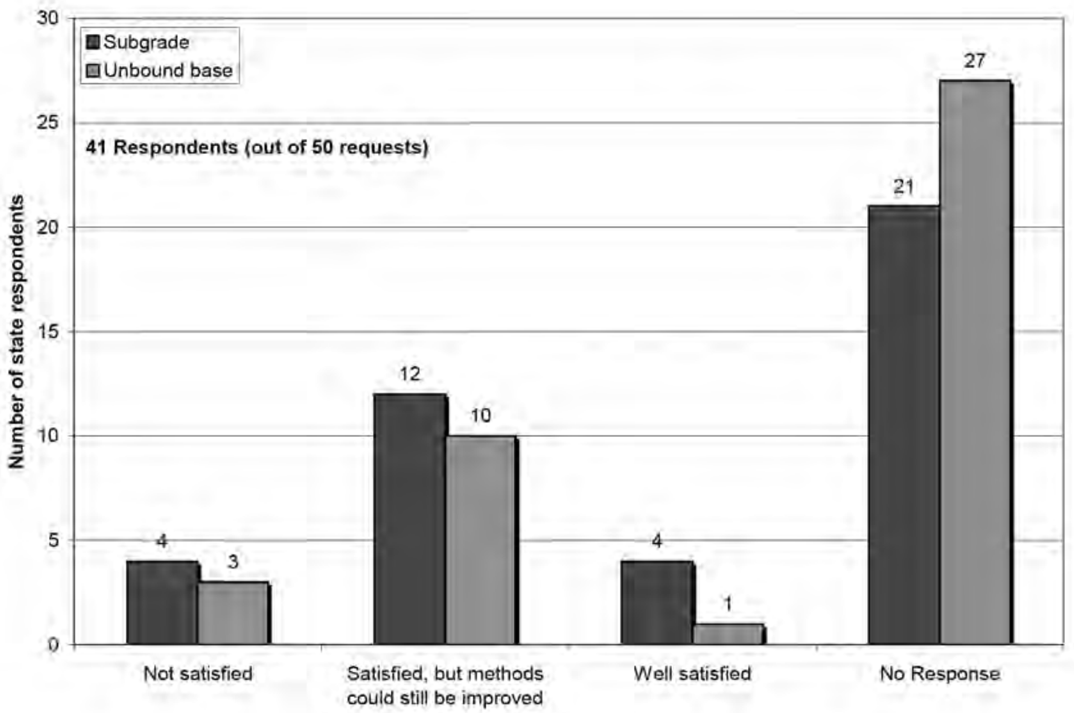


FIGURE 14 Responses related to satisfaction of methods to determine resilient moduli properties by state DOTs.

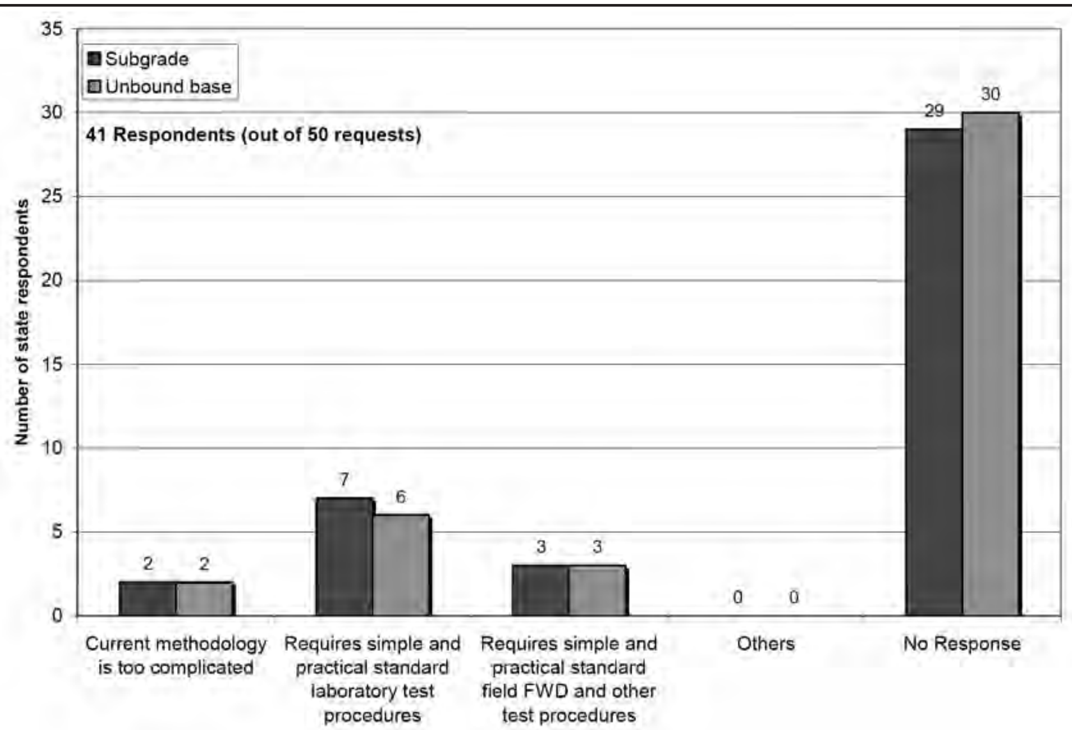


FIGURE 15 Reasons for being not satisfied with current methods.

the survey, uncertainty with new design guide, and other reasons. Nevertheless, the available responses show the need for certain actions items such as better technology transfer, more reliable test procedures without constantly changing them, developing correlations with a stronger database, defining the design moduli parameters more accurately, and providing simple yet practical procedures for implementation.

Pavement Group Survey Results

The survey was transmitted to 50 state DOTs, and a total of 40 responses were received (80%). The number 40 is used here as the total respondent number in the following analysis. A comprehensive summary of the survey results is provided in Appendix C. Important details from these survey analyses are presented in the following discussion.

Most of the respondents (24) mentioned that they use the "1993 AASHTO design guide to design pavements." This was followed by seven respondents who mentioned that they used the 1972 design guide. Figure 16 summarizes the response results. Apart from the standard design guides, a few state agencies, including Illinois, Washington, New York, Alaska, and Texas, mentioned that they use agency-developed procedures. One agency notably responded that it started using *MEPDG.*

The majority of respondents (18 for subgrades and 19 for bases) use resilient modulus obtained from different methods other than direct laboratory and field measurement. Indirect methods using CBR values, grain size and soil classifications, and *R* value for subgrades have been used in correlations to estimate moduli of both subgrade and unbound bases. Figure 17 shows respondent responses regarding the use of methods to determine resilient moduli for pavement design.

The majority of pavement group respondents (five) noted that they use a correction factor on FWD moduli to determine the M_R design value. Other respondents (six) noted that they provide input in various forms, including laboratory test-related procedural steps, which can be seen in Figure 18. Table 2 summarizes survey responses from pavement and geotechnical engineers.

Figure 19 shows the number of respondents that use various computer methods and programs to design flexible pavements. A total of 20 respondents noted that they use the DARWIN program to design pavements. Sixteen respondents use other methods, such as spreadsheets and other design guides, whose details are presented in Table 3.

Figure 20 depicts the number of respondents who consider seasonal variations in determining the resilient modulus. For determining the effective roadbed resilient modulus, three respondents use laboratory tests, four use FWD field tests, and 15 use other methods, which are summarized in Table 4. The total number of responses is higher than 40 because some respondents chose more than one option.

Figure 21 shows the number of respondents who use different methods for characterizing the structural coefficients and structural support of bases and subgrades. The major-

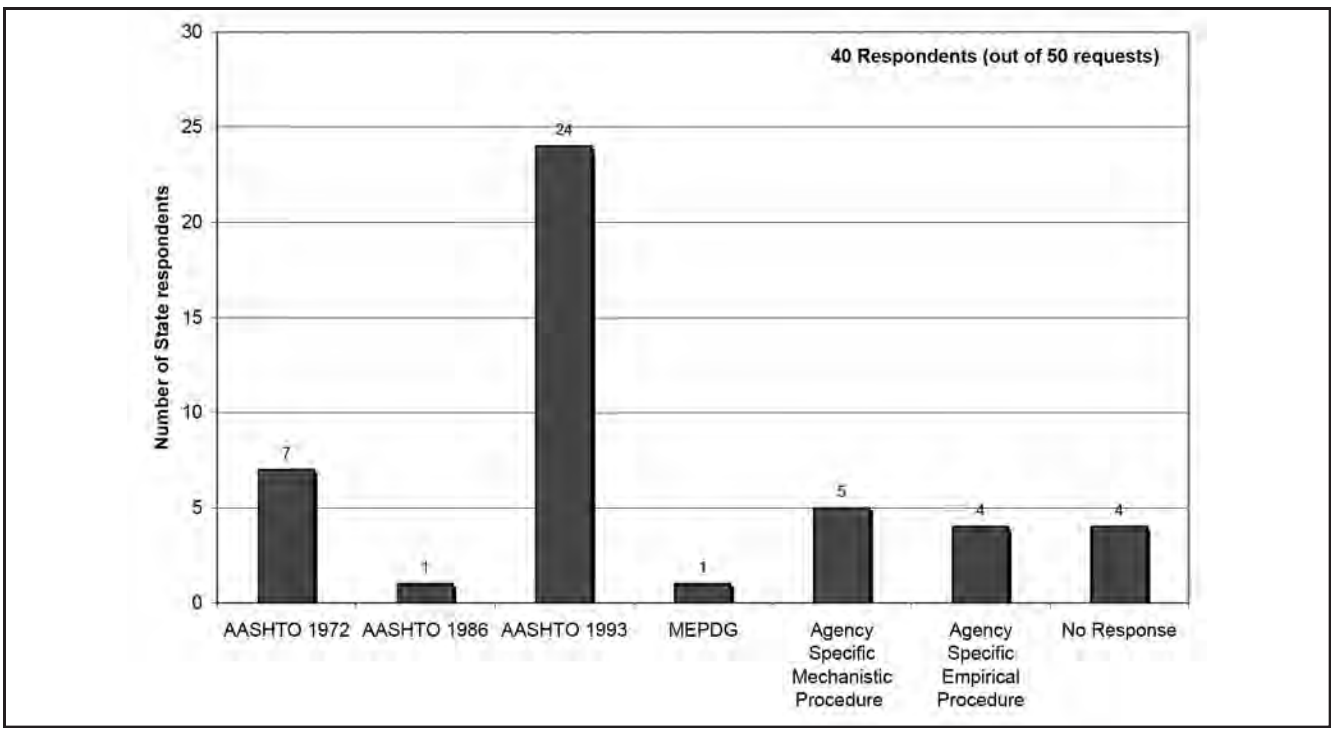


FIGURE 16 Methods used for designing pavements by state DOTs.

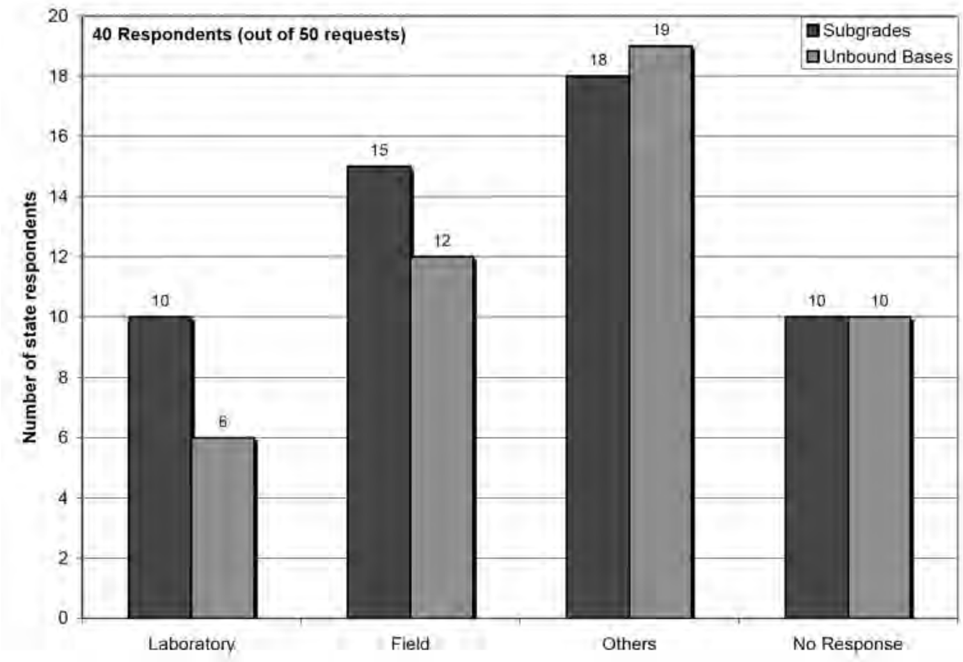


FIGURE 17 Procedures followed to determine design moduli by state DOTs for subgrades and unbound bases.

TABLE 2
DETAILS PROVIDED BY PAVEMENT ENGINEERS RELATED TO RESILIENT MODULUS PROPERTY DETERMINATION

Agency	Comments			
	Applied stresses in the laboratory	Moisture conditioning in the laboratory	Correction factor for M_R from the laboratory	Correction factor for M_R from FWD
Alabama	Axial stresses: 2, 4, 6, 8, and 10 psi	A-6 & A-7 soils on wet side of optimum	—	0.33
Florida	2 psi confining pressure	Optimum	No correction	Currently use 1.0 but we are researching
Kansas	—	—	—	0.33
Maine	—	—	—	0.29 (for Spring thaw)
Oklahoma	AASHTO T-307	Specimens at opt. moisture and at opt + 2%	—	—
New York	—	—	—	Yes , no specifics

ity of the respondents (17 for subgrades and 18 for bases) use local correlations, followed by those who used the 1993 AASHTO design guide to determine structural coefficients (six for subgrades and five for bases). More details on the methods followed are included in Appendix C.

Figure 22 presents the numbers of responses for various satisfaction levels derived from the use of resilient properties in the pavement design. The majority of the respondents (20 for subgrades and 12 for bases) are satisfied with the use of resilient properties in designing pavements. In comparison, these numbers are higher than those from the geotechnical survey.

The reasons for being not satisfied with using resilient modulus properties in pavement design are further explored and these responses are summarized in Figures 23 and 24 for subgrades and bases, respectively. The majority of respondents attributed reasons for their dissatisfaction to the complicated laboratory or field test procedures and complicated correlations required to determine the moduli of both subgrades and unbound bases. These responses are in agreement with those expressed by materials engineers. Action items mentioned at the end of the geotechnical survey are also valid in this case and are recommended for future implementation.

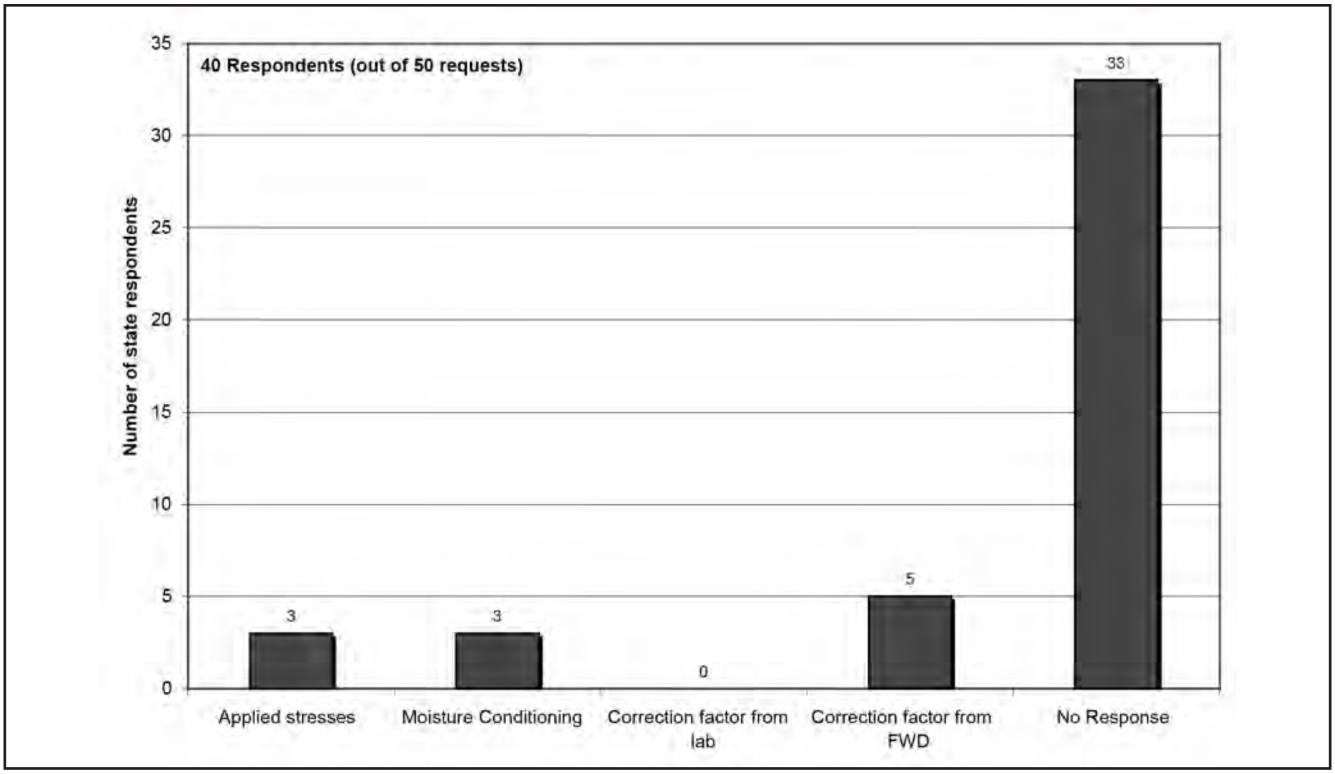


FIGURE 18 Responses on ‘Type of Input’ provided to materials/geotechnical engineers.

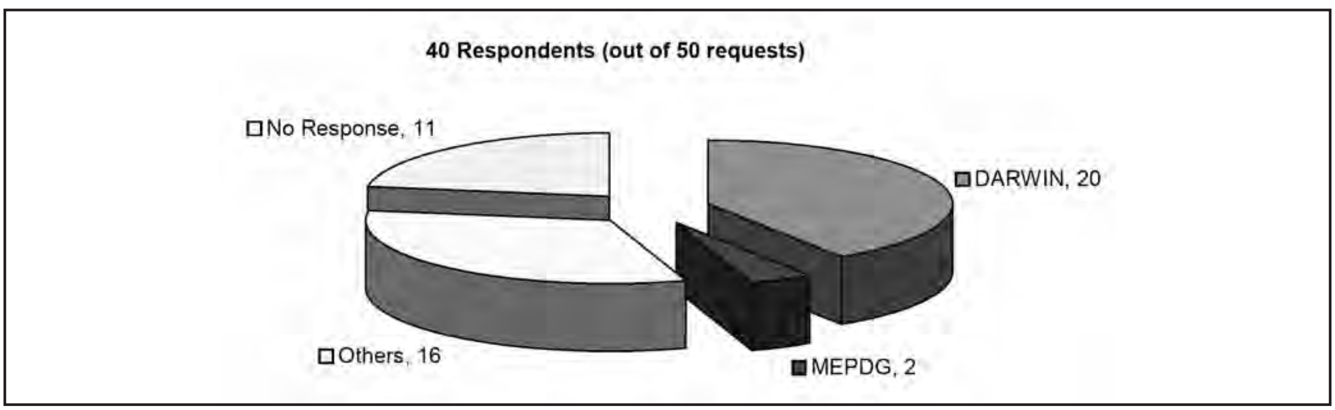


FIGURE 19 Number of respondents using various pavement design-related computer programs.

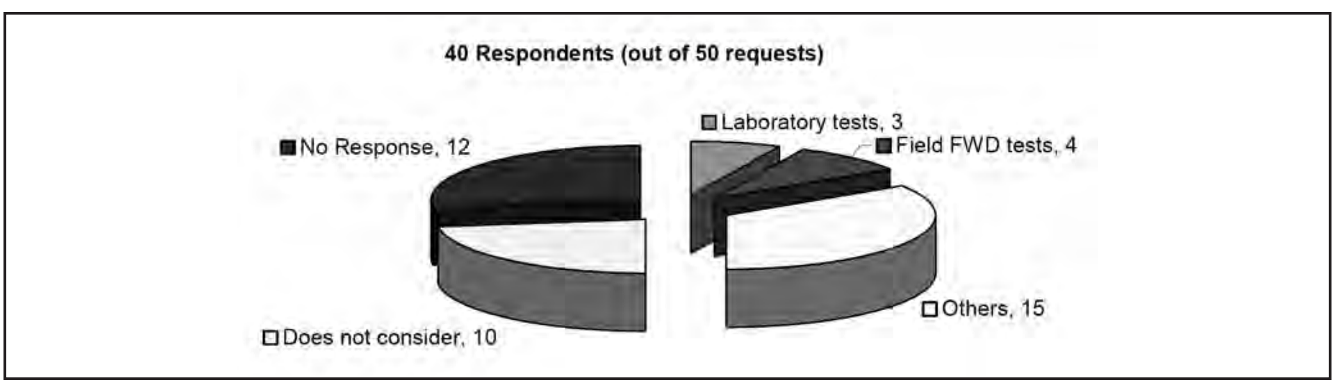


FIGURE 20 Percent respondents on how they considered seasonal variations in determining effective resilient modulus.

TABLE 3
RESPONSES RELATED TO COMPUTER METHODS USED IN DESIGNING PAVEMENTS

Agency	Comments
Alaska	ELMOD, AK Flexible Pavement Design Guide (2004)
California	Caltrans programs NewCon90 and CalAC
Florida	1998 Supplement to AASHTO rigid spreadsheet
Hawaii	Excel spreadsheet
Illinois	ILLI-PAVE
Minnesota	MnPAVE (for comparison to MnDOT method)
Mississippi	In-house for flexible, 1998 Supplement
New Hampshire	Excel spreadsheet
New York	NYSDOT Procedure
North Carolina	In-house spreadsheet
Ohio	ACPA’s AASHTO design software
Puerto Rica	ELMOD 4.5 FROM DYNATEST
South Carolina	Spreadsheet based on ‘72 Guide
Texas	FPS-19W
Washington	WSDOT developed M-E software (Everpave)
Wisconsin	WisPave

TABLE 4
RESPONSES ON HOW SEASONAL VARIATIONS WERE CONSIDERED IN DETERMINING EFFECTIVE RESILIENT MODULUS

Agency	Comment
Arkansas	Lowest value for material in saturated conditions
Alaska	Reduction factors are applied on the interpreted moduli
California	No consideration by our empirical method
Colorado	Engineering judgment
Illinois	Typical values
Kansas	Correlation with soil properties
Maine	By using a correction factor (0.29) on the interpreted moduli
Michigan	Spring time value is used
Minnesota	Design chart based on wet conditions
New Hampshire	Assume a ‘Soil Support Value’ of 4.5
New York	Seasonal subgrade & subbase moduli
North Dakota	FWD tests conducted in summer/fall
South Carolina	Minimal seasonal effects in our climate
Utah	Use worst case
Washington	Developed seasonal effects in-house

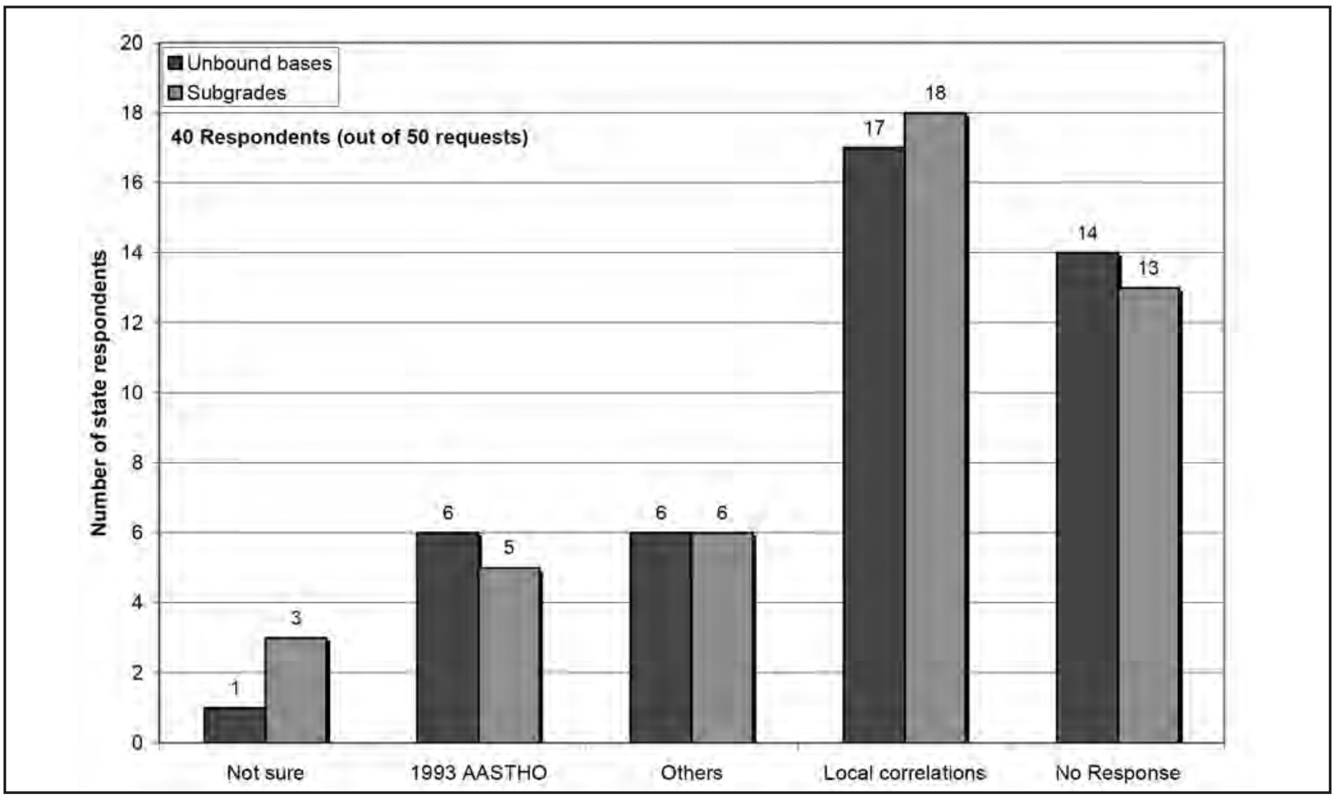


FIGURE 21 Percentage of respondents on how they characterize structural coefficient of unbound bases and structural support or number of subgrades.

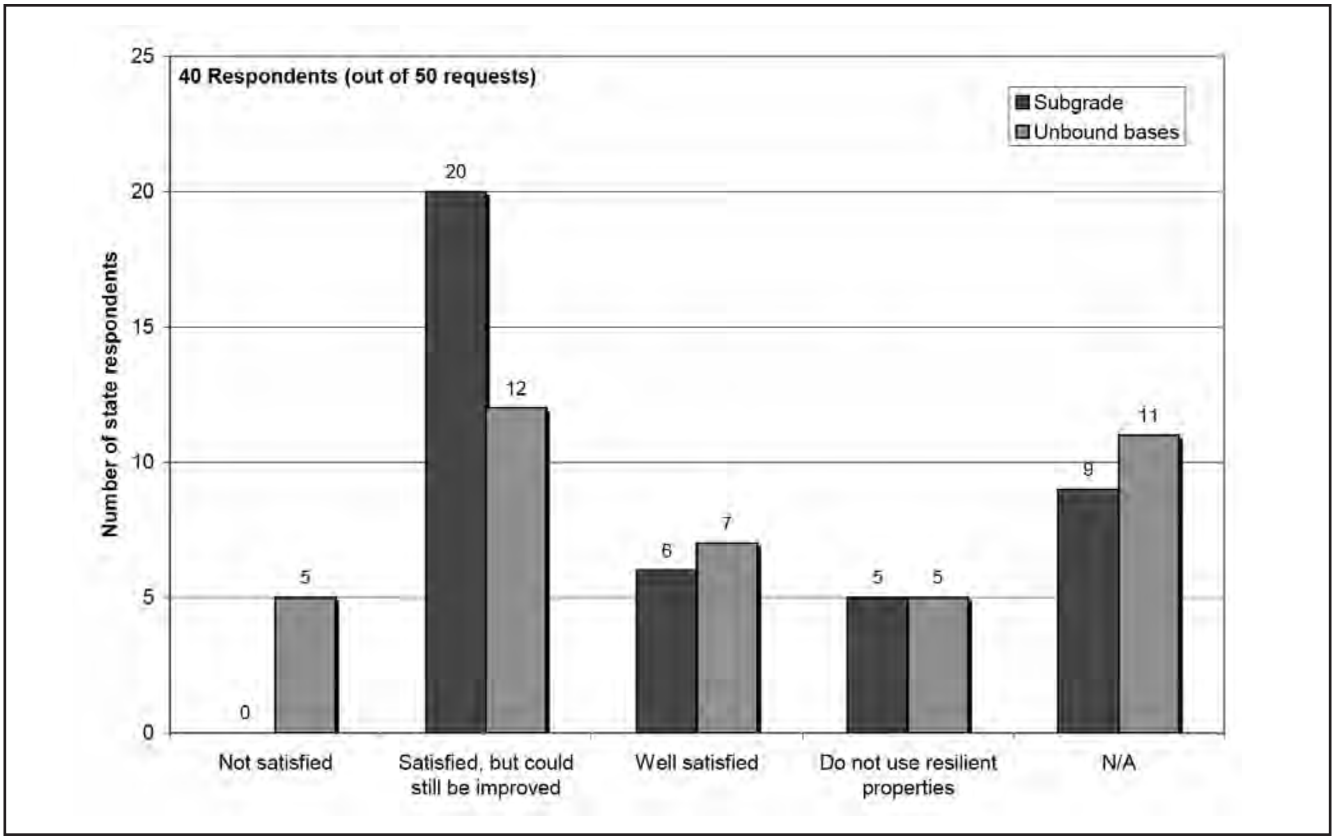


FIGURE 22 Responses related to satisfaction in using M_R properties to design pavements

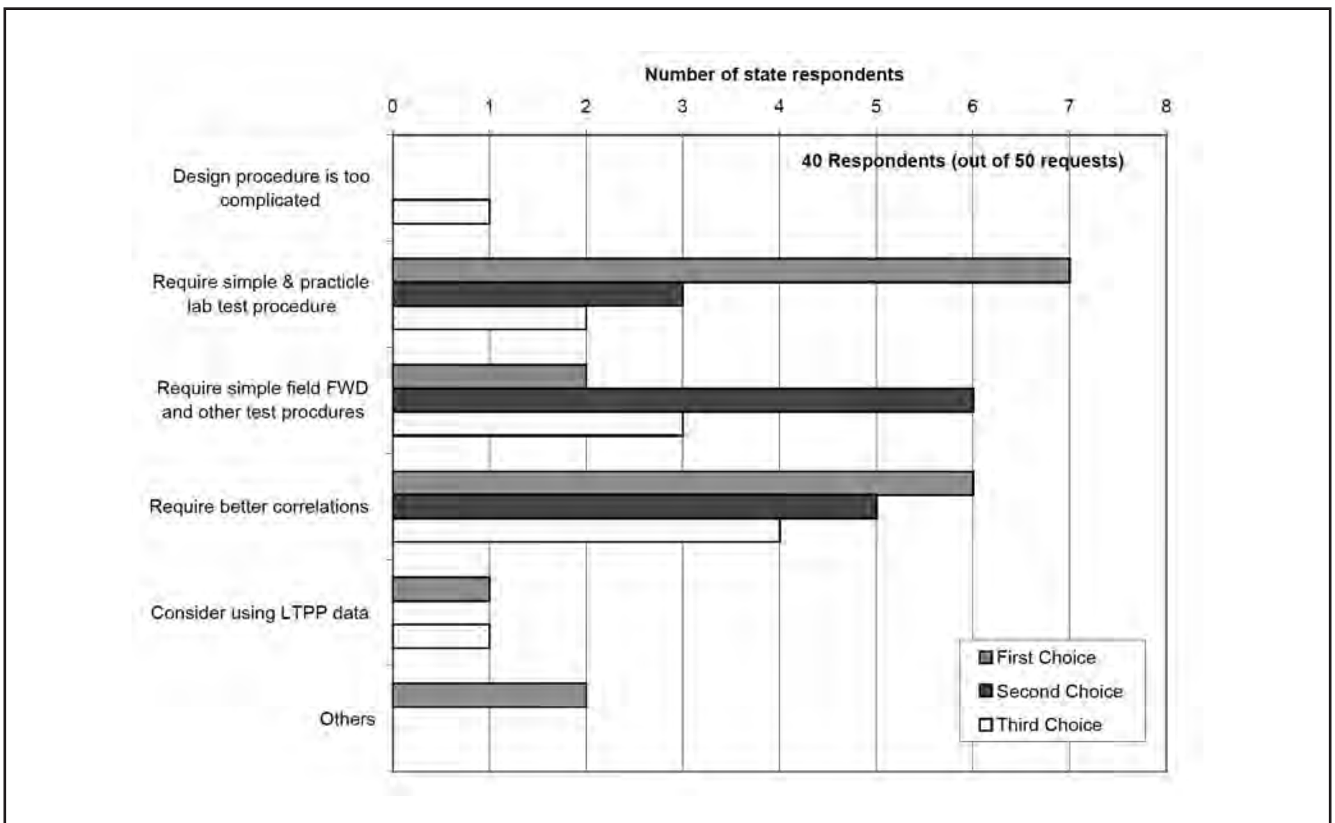


FIGURE 23 Reasons for not being satisfied (subgrade).

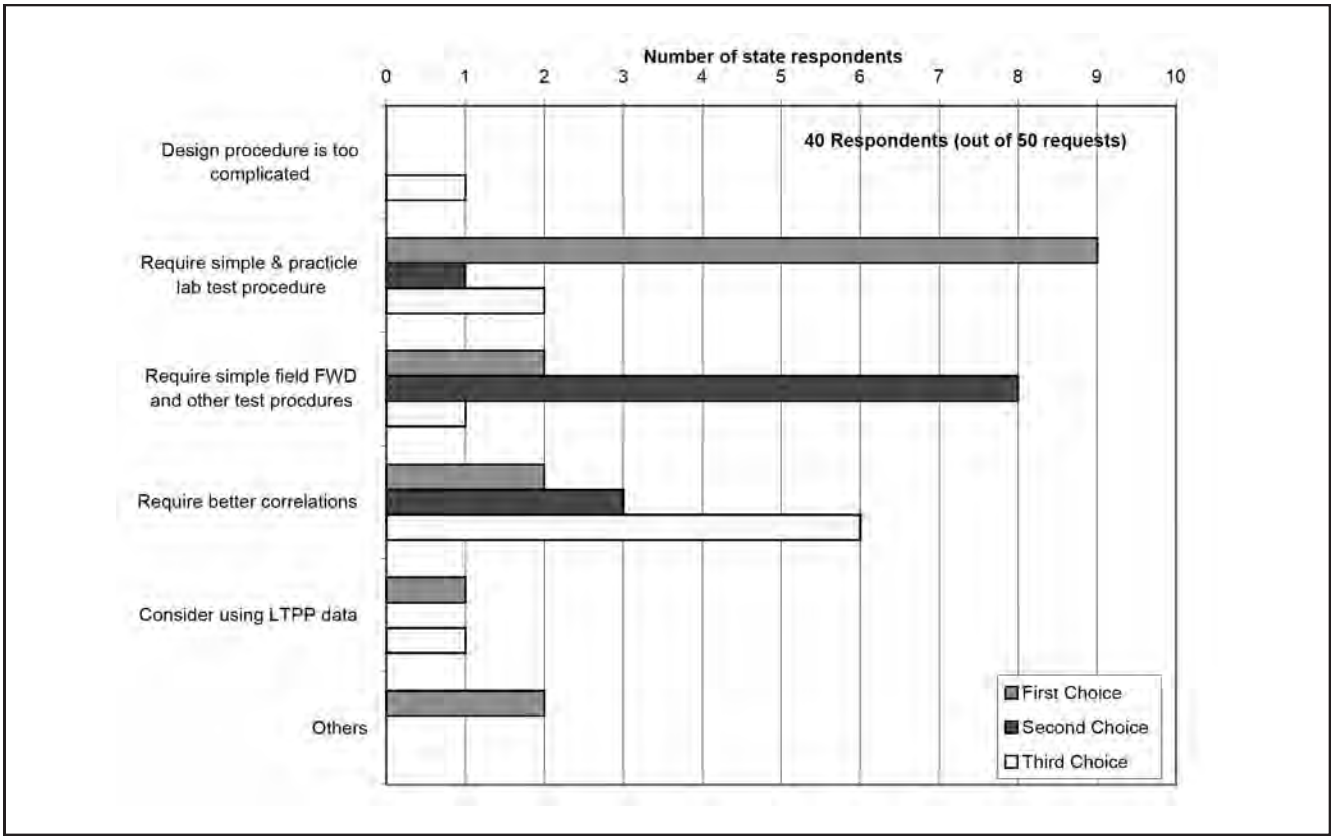


FIGURE 24 Reasons for not being satisfied (unbound bases).

SUMMARY

This chapter describes details from two Web-based surveys conducted from DOT engineers in Materials/Geotechnical and Pavement Design groups. The intent of these surveys is to learn the state of practice from these groups with respect to resilient modulus property determination of both bases and subgrades from various methods, including laboratory and field methods. The overall response to the surveys is impressive (more than 80% responded for both surveys). In the Geotechnical/Materials group survey responses, several respondents noted that they do not use or measure resilient moduli of soils from laboratory tests. Other responses show that some agencies determine M_R using various methods, including laboratory and field studies as well as correlations. The overall satisfaction of the respondents in the use of M_R for pavement design is low and several reasons, such as constant modification of test procedures, measurement difficulties, design-related issues and others, are attributed to the low level of satisfaction. In the Pavement group survey responses, similar issues are discussed along with the need to develop simple procedures to determine resilient property. Overall, both surveys provided valuable information that aided in the syntheses that summarize the various methods used to determine resilient property.

CHAPTER THREE

LABORATORY METHODS FOR MATERIAL STIFFNESS MEASUREMENT

INTRODUCTION

Chapters three, four, and five summarize the stiffness or resilient moduli–related literature information collected from various state DOTs. As a part of the literature review collection, several research reports from various states including Texas, Virginia, Louisiana, Kentucky, and Wisconsin were acquired and reviewed. Library search engines such as the Transportation Research Information Service (TRIS) and COMPENDEX were also used to collect other available documented information on the resilient modulus of subgrades and unbound material.

The collected literature was summarized in chapters three, four, and five in the following categories:

- Laboratory resilient moduli tests; test results of different types of subgrades and unbound pavement materials; advantages and limitations of laboratory tests (chapter three).
- Existing in situ nondestructive test methods for interpretation of resilient properties of unbound bases and subgrades; test results from a variety of subsoils; comparisons with the laboratory-determined resilient moduli properties; and advantages and limitations of these tests (chapter four).
- Existing in situ intrusive test methods for resilient property determination; test results for different subsoils; development of correlations between in situ data and moduli properties; and advantages and limitations of intrusive tests (chapter four).
- Direct expressions that correlate resilient moduli properties with basic soil properties and in situ compaction parameters; statistics of the correlations; advantages and fallacies of these correlations (chapter five).
- Indirect correlations that express model constant parameters (obtained from an analysis of various types of resilient moduli formulations including two-parameter "bulk stress and deviatoric stress" models to three- and four-parameter models) as functions of basic soil properties and compaction-related soil variables (chapter five).
- Matrix tables summarizing the literature findings (chapter five).

LABORATORY TESTS USED FOR RESILIENT MODULUS

Historical perspectives of the resilient modulus test procedure and its evolution are well documented by Ishibashi et al. (1984) and Vinson (1989). This paper presented at a resilient modulus workshop in Corvallis, Oregon, compares simple static load tests such as plate load test and CBR tests conducted from the 1960s to the 1990s as well as current RLT-related resilient modulus test procedures used after the 1980s to characterize subsoils for the flexible pavement design. The use of RLT tests in the place of static tests was attributed primarily to research efforts by Seed et al. (1962; 1967) the University of California, Berkeley. Other tests on aggregates can be found in the references cited by Saeed et al. (2001).

An earlier study conducted by Seed and McNeill (1958) documented the differences between initial tangent elastic modulus and resilient modulus and the need to develop laboratory procedures simulating in situ traffic loading conditions. After this study, several laboratory procedures were developed to determine the resilient modulus of subgrades and base aggregates. A brief discussion of these tests to determine M_R property is summarized here.

Repeated Load Triaxial Test

The Resilient Modulus test using RLT test equipment is designed to simulate traffic wheel loading on in situ subsoils by applying a sequence of repeated or cyclic loads on compacted soil specimens. Figure 25 shows an RLT testing system used to determine the resilient modulus of subgrades.

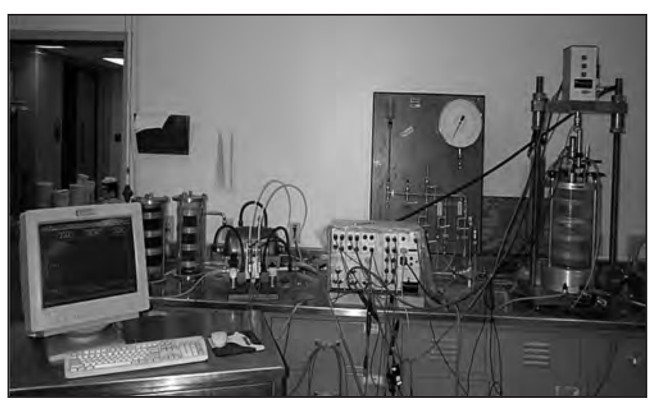


FIGURE 25 Triaxial unit with data acquisition and control panel unit.

The AASHTO T-307-99 method is currently followed for determining the resilient modulus of soils and unbound aggregate materials. Prior to this method, a few methods (namely, T-274, T-292, and T-294) were used. The stress levels for testing the specimens are based on the location of the specimen within the pavement structure. The confining pressure typically represents the overburden pressure on the soil specimen with respect to its location in the subgrade.

The axial deviatoric stress is composed of two components, the cyclic stress (which is the actual applied cyclic stress) and a constant stress (which typically represents a seating load on the soil specimen). The constant stress applied is typically equivalent to about 10% of the total axial deviatoric stress. The testing sequences employed for both granular and base or subbase materials and fine-grained subgrade soils are different, and these details can be found in AASHTO test standard procedures. A haversine-shaped wave load pulse with a loading period of 0.1 s and a relaxation period of 0.9 s is used in the testing. A haversine load pulse is recommended in the test procedure, which is based on the earlier AASHO road test research performed in the United States.

The test procedure involves preparation of a compacted soil specimen using impact compaction or other methods, transfer of soil specimen into triaxial chamber, application of confining pressure, and then initiation of testing by applying various levels of deviatoric stresses as per the test sequence. The test process requires both conditioning followed by actual testing under a multitude of confining pressure and deviatoric stresses.

At each confining pressure and deviatoric stress, the resilient modulus value is determined by averaging the resilient deformation of the last five deviatoric loading cycles. Hence, from a single test on a compacted soil specimen, several resilient moduli values at different combinations of confining and deviatoric stresses are determined. From these values, the design resilient modulus value can be established by determining the M_R value at appropriate confining pressure and the deviatoric stress levels corresponding to the subgrade and unbound base layer location within the pavement system.

Resonant Column Test

The resonant column (RC) test was initially developed to study dynamic properties of rock-like materials in the early 1930s. The technique has since been upgraded continually for dynamic characterization of a wide variety of geologic materials (Huoo-Ni 1987). The test can be simulated as the fixed-free system. The specimen rests on a pedestal and both the top cap and torsional drive plate are securely attached onto the top end of the specimen. During RC testing, the drive plate is allowed to rotate freely such that a torsional excitation can be applied at the top end of the specimen with a constant amplitude and varying frequency. Variations of the peak torsional displacement with frequency are then recorded to obtain the frequency response curve. Peak displacements are recorded through an accelerometer attached to the drive plate. Test procedure details can be found in Stokoe et al. (1990).

The frequency response curve generated during the test can then be displayed on the analyzer main screen for post-test data processing. The small-strain shear modulus G can then be calculated as follows (Richart 1975):

$$G = \rho(2\pi L)^2 \left[\frac{f_r}{F_r}\right]^2 \qquad (1)$$

$$F_r = \sqrt{\frac{I_R}{I_o}} \qquad (2)$$

where G is small-strain shear modulus, ρ is soil density, L is sample length, f_r is resonant frequency, F_r is driver constant, I_R is polar moment of inertia of soil column, and I_o is polar moment of inertia of driver system.

The small-strain shear modulus is then converted to resilient modulus values by using the following Equation 3 with an assumed Poisson's ratio.

$$E = 2\,G\,(1+\mu) \qquad (3)$$

Barksdale et al. (1997) noted some concerns with the RC testing as a result of low axial strains applied during the testing, which are assumed to be much smaller than the strains applied under heavy wheel loads applied near the surface. Resilient strains applied under wheel loads are small and comparable with the strains recorded in this test.

Simple Shear Test

It is well known that the stresses in subsoil undergo stress reversals owing to traffic wheel load movements, which can be seen in Figure 26. In a simple shear test, the soil specimen will be subjected to such state of stresses and hence considered to be a more representative test for the determination of resilient moduli of soils. However, Barksdale et al. (1997) noted that the stress paths of the soil specimen in the laboratory and the in situ soil in the field are different.

In this test, a soil specimen is subjected to a shear stress in both directions. Though this method was used for both resilient moduli and permanent strain measurements, there are still some concerns that limit the adaptation of this method. These are the stress-induced anisotropy of the soil specimen resulting from shear stress application, and the difficulty in applying uniform stress.

Hollow Cylinder Test

A hollow cylinder test simulates stress conditions close to the field traffic loading, including the principle stress rotations taking place in the subgrade caused by wheel load movements (Barksdale et al. 1997). In this test, a hollow cylindrical soil specimen is enclosed by a membrane both inside and outside the sample. Stresses are applied in axial or vertical, torsional, and radial directions. Repeated loads can be simulated in this setup and related moduli can be determined. Because of the possible application of various types of stresses, different stress path loadings simulating field loading conditions can be applied. Also, this setup can be used to perform permanent deformation tests.

A few other tests, including the Cubical Triaxial Test, are used in the literature. These tests are still under research evaluation, however, and they are yet to be used for practical applications. Other test methods that provide parameters that are linked with moduli or stiffness properties of soils include the CBR test, *R* value test, Texas triaxial value, and SSV test. These methods employ static loading of the soil specimens until the failure, and the properties measured in the tests are reported as CBR, *R*, or SSV values. Because of the availability of large test databases of these properties, various state agencies developed correlations between the AASHTO-recommended moduli of soils with the CBR, *R*, or SSV values. Details on these correlations are presented in chapter five.

As noted previously, several test methods have been used to determine the resilient modulus of subsoils in the laboratory conditions. However, the most prominent method for a laboratory modulus test has been the RLT test, primarily because AASHTO standardized this test and it features better simulation of pavement subgrades under traffic loading. The next section discusses several research studies that utilized these tests and their findings.

LABORATORY M_R TESTS—SUMMARY

A thorough review of several research reports and papers on resilient modulus testing of subgrades and unbound bases in the laboratory conditions was next made. Several research reports and articles have been published pertaining to this topic. These papers and reports cover laboratory procedures and findings as well as a few pavement design recommendations.

The investigator collected various state research reports that primarily describe DOT-funded research and how M_R tests and their results are applied for the mechanistic pavement designs in the respective states. Additional information was also sought from the states during the surveys, which resulted in a few additional reports. Overall, resilient moduli test results from the literature are presented in three phases:

- First phase: reported before 1986
- Second phase: reported from 1986 to 1996
- Last phase: reported after 1996

In 1986, the AASHTO interim design guide recommended the use of resilient modulus to characterize subgrades and bases for flexible pavement design. The starting year of 1996 is randomly chosen for the last phase, because any reports presented after that year are considered to be recent literature (that is, literature presented in the last 10 to 11 years).

M_R Literature Before 1986

In a 1989 workshop on the application of resilient modulus in pavement design, Vinson presented a comprehensive review of the resilient modulus test work performed at the University of California Berkley in the early 1960s. This paper primarily includes the research performed by Seed et al. (1962), which focused on one of the earliest works on resilient modulus measurements of subgrade soils at various compaction conditions and soil types. Other studies performed

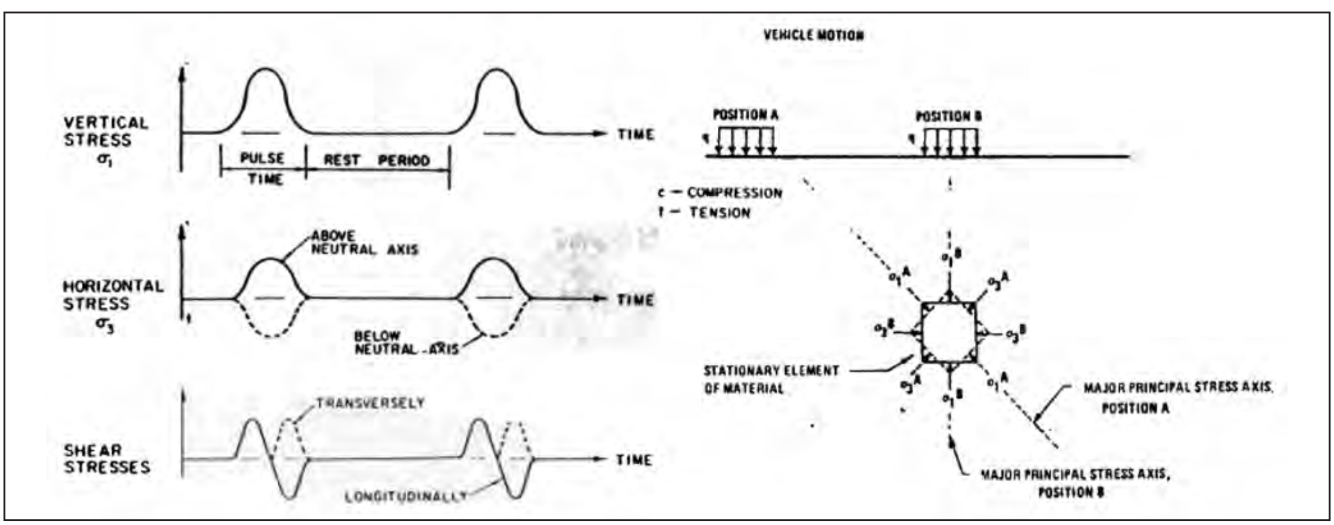


FIGURE 26 Stresses under traffic wheel load and stress reversal under wheel loading (Vinson 1989; Barksdale et al. 1997).

by Barksdale (1971, 1972) and Terrel et al. (1974) addressed laboratory-related variables including the shape of the loading pulse and duration of the laboratory test formulation.

Hicks and Monismith (1971) later described several factors that influence the resilient properties of granular materials including bases. Kalcheff and Hicks (1973), then documented the resilient moduli tests performed on granular soils including unbound aggregates. This study described the potential stress sequence and stress ratios recommended for testing granular materials. Hull et al. (1980) reported M_R test results on base materials following the test procedures recommended by Kalcheff and Hicks (1973). Allen and Thompson (1974) addressed the response of lateral stresses on resilient properties of granular materials.

In 1976, Thompson and Robnett studied resilient properties of several Illinois subgrade soils at the University of Illinois, Urbana, and this study reported the test results and the development of correlations between resilient modulus and subgrade soil properties. They proposed an arithmetic model to describe the resilient properties of fine-grained soils. Shook et al. (1982) later discussed an Asphalt Institute method of designing flexible pavements in which a bulk stress model was used to model the resilient behavior of cohesionless soils. Uzan (1985) explained the limitations of the bulk stress model with two model constants and then introduced a two-parameter model consisting of both bulk and deviatoric stresses with three model constants to simulate the resilient behavior of subsoils.

Hence, it can be summarized that the research to 1986 mostly focused on (1) the development of test procedures and equipment modifications to test cohesive subgrades and granular base materials, (2) the development of appropriate models to represent the resilient behavior, and (3) the introduction of a few correlations based on soil properties to predict resilient properties.

M_R Literature Between 1986 and 1996

Following the recommendation by the 1986 AASHTO interim design guide to use resilient modulus property for pavement material characterization, several research studies were initiated with the support of several DOTs. A few of these studies and their findings are summarized in Table 5.

TABLE 5
FINDINGS FROM RESEARCH REPORTS AND PAPERS ON RESILIENT MODULUS DURING 1986–1996

References	Description of Research	Summary and Findings
Elliott et al. (1988) Elliott (1992) Arkansas DOT	Resilient Properties of Arkansas Subgrades	Repeated load triaxial (RLT) test setup and AASHTO T-274 procedure were used for performing laboratory resilient moduli tests. Kneading and static compaction methods were followed for preparing compacted soil specimens. Percent moisture content was varied between 70% (dry of optimum) to 130% (wet of optimum). Resilient moduli decreased with an increase in moisture content.
Workshop on Resilient Modulus Testing, Oregon State University, Corvallis, Oregon (1989)	An overview of Resilient Modulus Test and its Significance	A few of the following presentations were made at this workshop: Vinson—Past work and current status Ho—Florida DOT Experience Thompson—Factors affecting M_R of Subgrades and Granular soils
Woolstrum (1990) Nebraska Department of Roads	Resilient Properties of Nebraska Subgrades and Aggregates (14 of them)	RLT test setup and AASHTO T-274 procedure were used. Conditioning was done with 15,000 cycles of a haversine loading. Loading period of 0.1 s and a relaxation period of 0.4 s were applied. Aggregates were tested as per granular material test procedures. Three compaction moisture conditions, optimum, wet, and dry of optimum were studied. Expected trends of decrease in resilient moduli with an increase in moisture content. Correlations between M_R and Nebraska group index parameter were developed.
Claros et al. (1990) Stokoe et al. (1990) Pezo et al. (1992) Pezo and Hudson (1994) Texas Department of Transportation	Test Procedure Development, Calibration and Evaluation of M_R Equipment and Modeling of Resilient Properties	RLT test setup and AASHTO T-274 (sample preparation) and P-46 procedure protocols (testing) were used on synthetic and subgrade and aggregate samples for performing laboratory resilient moduli tests. Comparisons were made with torsional ring shear and resonant column test data, which showed some variations. Synthetic samples provided a good methodology to calibrate the M_R equipment. Pezo's study on different subgrades of Texas with different PI values showed that an increase in moisture content resulted in the decrease of M_R values. A TxDOT model with seven correction factors was developed to predict resilient properties.

continued

TABLE 5 (*continued*)

References	Description of Research	Summary and Findings
Wilson et al. (1990) Ohio DOT	Multiaxial Testing of Ohio Subgrade	Seven subgrade soils were taken from different sites. Specimens were compacted in cubical mold of 4 in. x 4 in. x 4 in. Cyclic tests were conducted after 200 cycles of conditioning. Resilient response was dependent on compaction moisture content. At low stress ranges, M_R decreases with an increase in deviatoric stress.
Ksaibati et al. (1994) Ksaibati et al. (2000) Wyoming DOT	Factors Influencing M_R Values of Subgrades	Nine subgrade soils were taken from different regions of Wyoming. RLT test and AASHTO TP-46 or T-294 were used. FWD tests were conducted at the sampling sites and results were analyzed with backcalculation programs. Moisture content influenced resilient properties of A-4 and A-6 soils. EVERCALC program predictions appear to give accurate resilient moduli.
Mohammad et al. (1994, 1995, 1999) Puppala et al. (1997, 1999) Louisiana DOT	Resilient properties of Louisiana Subgrades	RLT test method was used for M_R tests. T-292 and T-294 as well as internal and external displacement measurements were evaluated in providing realistic and repeatable resilient properties of silty clay and sandy soil. Six different soils from different regions of Louisiana were sampled and tested in the RLT using T-294 procedure. Five compaction moisture conditions were studied. RLT test and AASHTO TP-46 or T-294 were used. Correlations between resilient moduli and soil properties were developed.
Drumm et al. (1990) Drumm et al. (1995) Andrew et al. (1998) Tennesse DOT	Resilient response of Tennessee Subgrades and effects of post-compaction saturation on resilient response of subgrades	Eleven subgrades were taken from different regions of Tennessee. Compact densities as per standard Proctor compaction and specimen preparation as per kneading method. P-46 method and RLT tests were followed. Optimum moisture content condition and moisture content condition close to 100% saturation were studied. Saturation resulted in the reduction of resilient moduli. Saturation related reductions are highest in A-7-5 and A-7-6 soils than in A-4 and A-6 soils. A methodology to correct the resilient modulus due to increased degree of saturation was developed.
Zaman et al. (1994) Chen et al. (1995) Daleiden et al. (1994) Oklahoma DOT	Assessment of Resilient Modulus Tests and Their Applications for Pavement Design	Resilient modulus testing using RLT test was performed. Six different aggregate sources were taken from different locations from Oklahoma. T-292 and T-294 procedures were used for M_R testing. Compactions were done at optimum and 95% of optimum dry density. Resilient moduli of aggregates varied between 41 and 262 MPa and these results are lower than those reported in the literature at that time. Variability in M_R due to test procedure appears to be higher than that of aggregate source.
Santha (1994) Georgia DOT	Resilient Moduli of Subgrade Soils from Georgia	Soils from 35 sites were studied. RLT equipment and T-274 procedure were used. M_R results varied considerably due to variations in soil types and compaction conditions. Soil type, compaction conditions, and Atterberg limits were used as independent variables for M_R correlations.

Elliott et al. (1988) reported resilient moduli test results obtained on different cohesive subgrades in Arkansas. The main intent of this research was to explain the effects of field moisture content on the resilient moduli of compacted subgrades. This study also addressed the effects of compaction procedures and moisture content variation on the resilient moduli properties. Figure 27 presents the variation of resilient modulus of fat clay (CH) from Jackport, with respect to percent changes in optimum moisture content. A decrease in the M_R value close to 1 ksi was reported for percent increase in the optimum moisture content. A low percent of optimum (below 100%) was termed as dry of optimum and a high percent of optimum (above 100%) was termed as wet of optimum conditions. Similar findings were reported on other cohesive subgrades in this study.

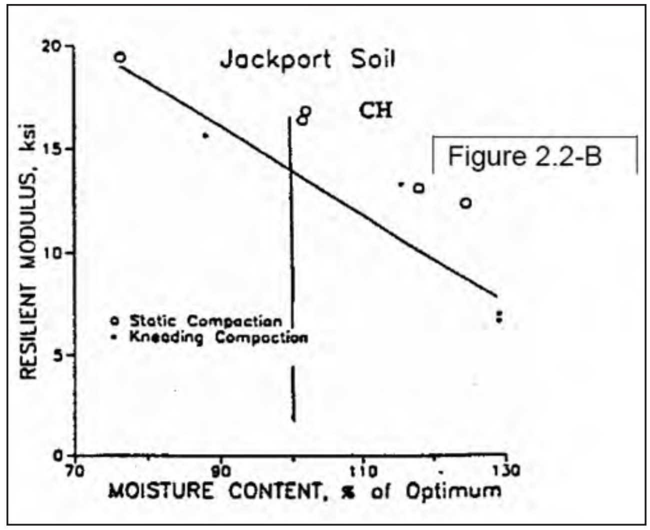


FIGURE 27 Resilient modulus of CH soil from Arkansas versus percent optimum moisture content (Elliott et al. 1988).

In 1989, a workshop on resilient modulus was held at Oregon State University in Corvallis and several researchers, practitioners, and equipment manufacturers discussed various testing, design, and equipment-related aspects of resilient modulus testing. This workshop was instrumental in leading several DOTs to start research on the resilient moduli response of their local soils.

Woolstrum (1990) studied 14 different Nebraska soils and yielded similar conclusions to those of Elliott et al. (1988). This study also developed correlations by introducing a Nebraska group index parameter (G) as an independent variable. The AASHTO T-274 procedure was used to determine resilient properties of local soils. Several research papers and reports were published in the early 1990s that focused on the resilient modulus research performed in the state of Texas (Claros et al. 1990; Pezo et al. 1992). These studies show calibration of RLT test devices, use of other equipment including RC and torsional ring shear devices to measure the shear modulus, and estimating elastic or resilient modulus. Pezo et al. (1992) focused on a universal model development to predict resilient properties of subsoils.

Research studies funded by Texas DOT (TxDOT) have evaluated the use of synthetic material samples for calibrating various moduli measurement devices, including RLT, RC, and torsional ring shear devices (Claros et al. 1990; Stokoe et al. 1990; Pezo et al. 1992; Pezo and Hudson, 1994). Figure 28 presents typical test results conducted on cohesive subgrade soil as per the TP-46 procedure.

Another study performed by Stokoe et al. (1990) addressed the use of other devices such as the RC test to measure moduli of calibrated synthetics specimens. Figure 29 presents a comparison of axial strains generated from RC testing with those generated using RLT tests while calibrating the medium stiff and stiff urethane materials. Both stiff and medium stiff materials (TU-960 and TU-900) extended over the majority of the M_R range determined from AASHTO T-274 RLT testing, whereas the soft material (TU-700) extended over half of the range reported by the RLT testing. This research also evaluated resilient or stiffness properties of subgrades from different parts of Texas and also developed a universal model.

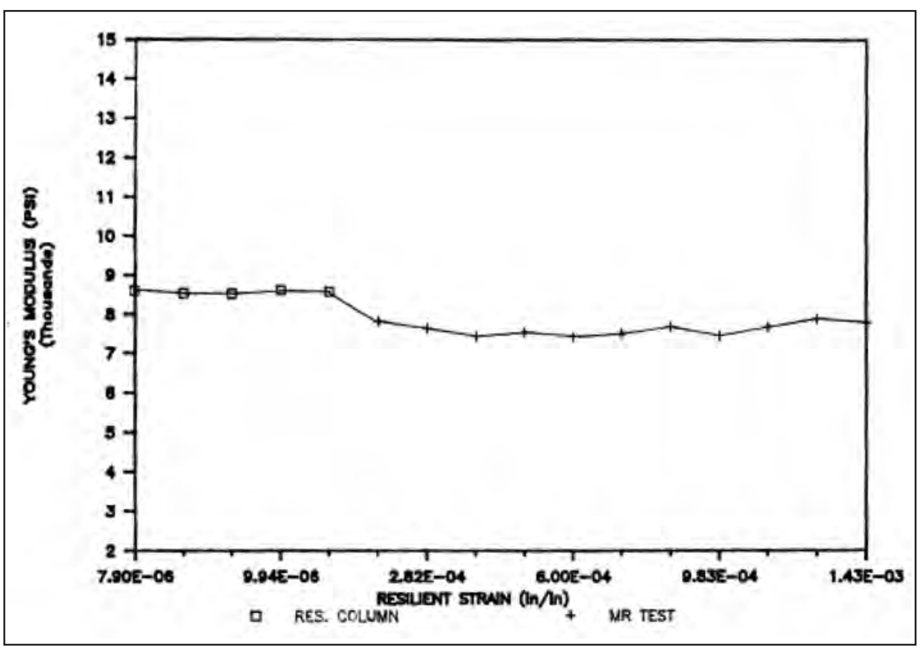


FIGURE 28 Moduli test results on synthetic sample from resonant column and RLT tests (Claros et al. 1990).

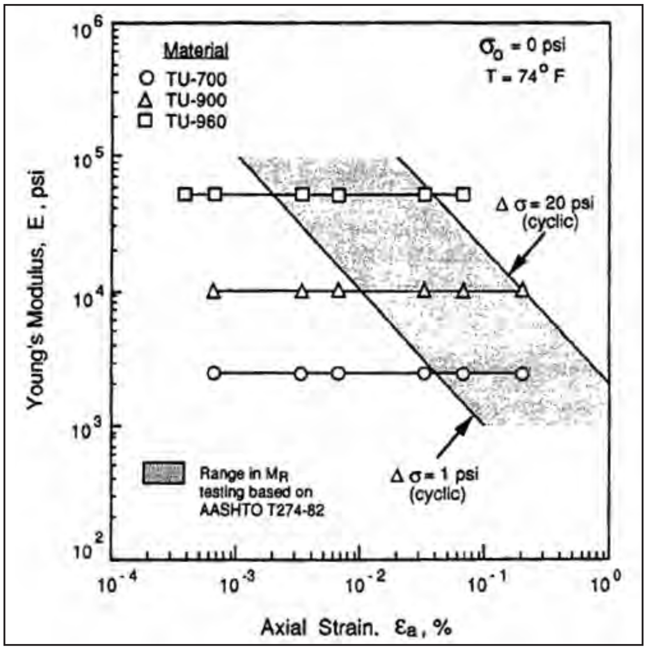


FIGURE 29 Comparisons of axial strains measured from RLT and resonant column tests (Stokoe et al. 1990).

Wilson et al. (1990) presented research findings on Ohio subgrades in which resilient properties of subgrades were measured using a multiaxial cubical triaxial test setup. Figure 30 presents a multiaxial testing device used in this research. Researchers noted the uniqueness of this equipment by applying stresses in all directions and concluded that this equipment was capable of providing resilient properties of subgrades. The test procedure used in this research was unique, and it included application of one level of confining pressure of 5 psi and different deviatoric stresses ranging from 1 to 8 psi. The deviatoric stress pulse was applied at a rate of 1 pulse/s. Resilient properties were determined based on the measured strain response.

Typical test data on a granular subgrade are presented in Figure 31, which shows the influence of deviatoric stress and

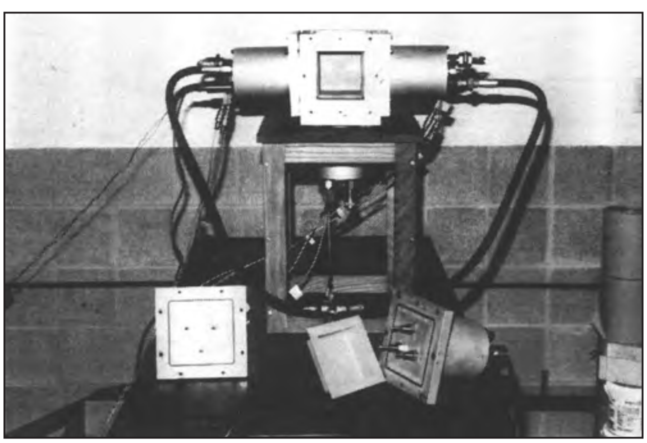


FIGURE 30 Photograph of multiaxial testing device (Wilson et al. 1990).

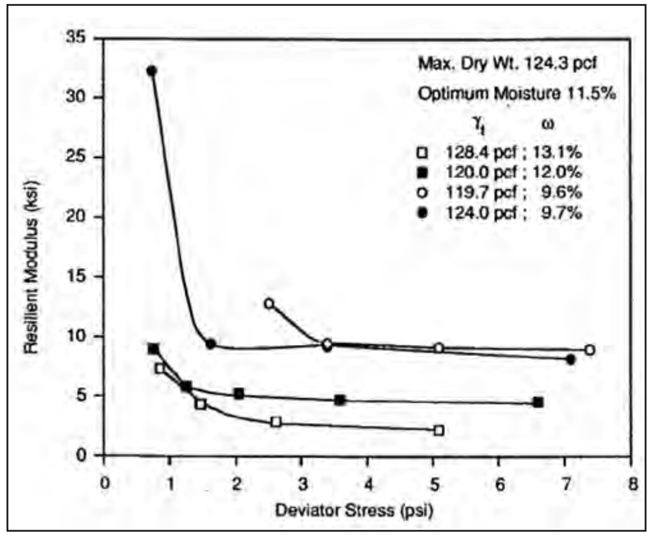


FIGURE 31 Resilient moduli results of granular subgrade from Ohio (Wilson et al. 1990).

compaction moisture content on the resilient moduli properties. These results indicate that an increase in deviatoric stress resulted in a decrease in resilient moduli properties. Also, an increase in compaction moisture content resulted in a decrease of resilient moduli of granular soils.

Burczyk et al. (1995) reported resilient properties of Wyoming subgrades. An RLT test setup and AASHTO T-294 procedure were used in this study, which also discussed various fundamental soil properties that influence resilient properties of subgrades in Wyoming. This study also evaluated various backcalculation methods used to interpret the resilient properties.

Mohammad et al. (1994a,b, 1995) described the resilient properties of Louisiana subgrades, including a complete evaluation of RLT setup and AASHTO test procedures T-292 and T-294, as well as measurement systems including linear variable differential transformers (LVDTs) placed for the middle third of the specimen (referred to as middle) and at the ends of the soil specimen (referred to as end), both being internal deformation measurement systems in yielding reliable resilient properties. Figure 32 presents resilient moduli determined from both internal measurement systems of a sandy specimen tested in the research. Higher moduli values were measured from the middle LVDT system than the end LVDT system. The ratios between M_R measured from the middle system to the end system varied from 1.15 to 1.22 at different compaction moisture content, indicating a 15% to 20% increase in moduli values obtained with the middle measurement system.

Drumm et al. (1990, 1997) studied resilient moduli of different types of subgrades from Tennessee using a SHRP P-46 test procedure. Research was focused on the resilient moduli data development for Tennessee subgrades, and also

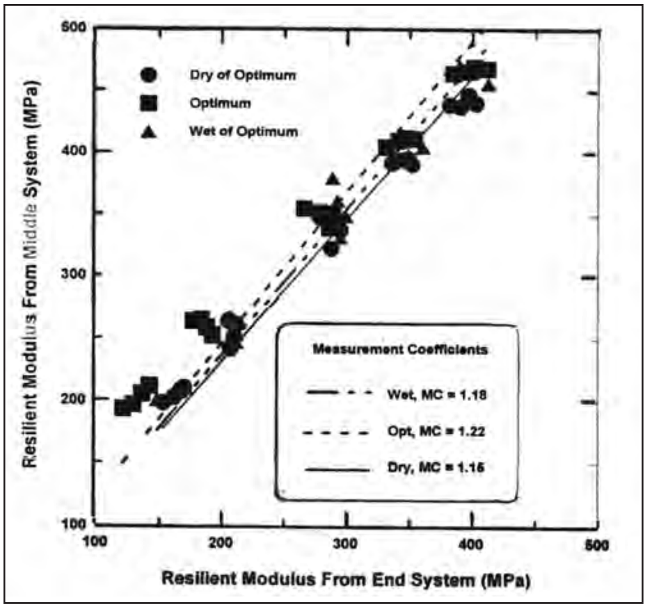


FIGURE 32 Resilient moduli results measured from both end and middle deformation measurement system (Mohammad et al. 1994a,b).

addressed the reductions in resilient moduli with respect to post-compaction saturation. Figure 33 presents the effects of post-compaction moisture content in terms of degree of saturation on the resilient modulus of subgrades. As expected, an increase in saturation resulted in a decrease in M_R values. This research also led to the development of regression models for prediction of resilient properties of subgrades. These details are presented in chapter four.

In the early 1990s, Thompson and Smith (1990), Zaman et al. (1994), and Chen et al. (1994) reported the resilient moduli of unbound aggregate bases using AASHTO T-292 and T-294 procedures. Variations of moduli with respect to test procedures and aggregate types are explained in these studies. Figure 34 presents the effects of test procedures on the resilient properties of aggregates from Choctaw and Murray counties in Oklahoma. Test results indicate that AASHTO's T-294 procedure yielded higher moduli than its T-292 procedure, and this variation was attributed to stress conditioning and stiffening effects in the T-294 procedure. Also, this study reported that the M_R variability with respect to test procedure was higher than the same with respect to aggregate source.

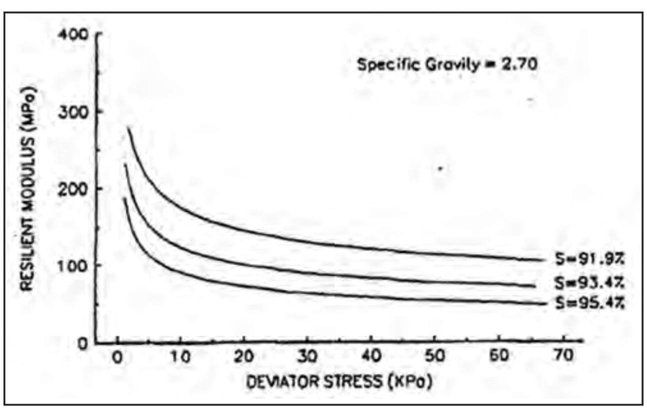


FIGURE 33 Influence of post-compaction moisture content on resilient moduli results (Drumm et al. 1990, 1997).

Santha (1994) studied the resilient properties of subgrades from 35 test sites in Georgia, using T-274 procedure. These results show wide variations in M_R with respect to soil type and compaction procedures used in the testing. The measured data were used and analyzed with two-parameter and three-parameter models. The three-parameter model captured the measured resilient properties better than the two-parameter model. Further discussion on these test results and their use in the development of multiple linear regression analyses of test results is presented in later sections.

Overall, it can be summarized that the resilient modulus research performed between 1986 and 1996 focused on the use of various laboratory and field equipment to determine the resilient properties of both subgrades and bases. Several test procedures (T-292, T-294, and P-46) were introduced and evaluated during this phase. Displacement measurement systems, one in the middle third of the soil specimen and one at the ends of the soil specimen were researched to provide realistic M_R values. Also, a few of these studies investigated and tested various local subgrades and unbound bases for developing a database of resilient properties. The measured data were later used to develop various models to predict resilient properties of subgrades and aggregates. Table 6 provides a summary of the literature findings from 1986 to 1996.

M_R Literature After 1996

Modifications of AASHTO test procedures from T-294 to T-307 with different testing-related specifications occurred during this phase. This resulted in additional research being

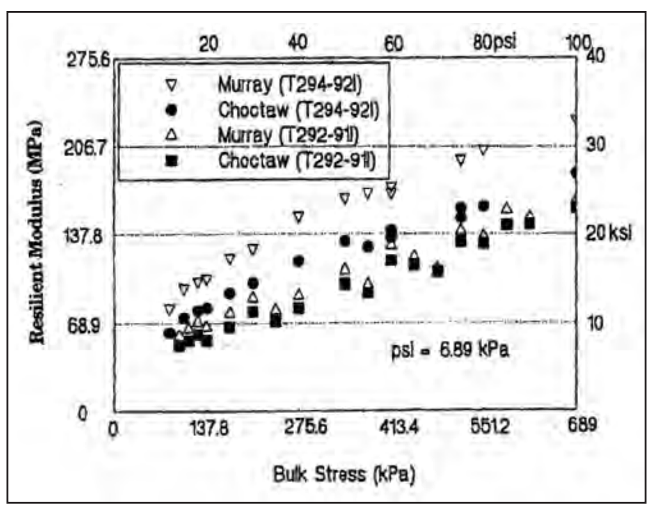


FIGURE 34 Influence of AASHTO test procedure on resilient moduli results of aggregate resources (Chen et al. 1994).

TABLE 6
SUMMARY OF MAJOR FINDINGS ON RESILIENT MODULUS FROM '1986 TO 1996'

Topic	Observations
Equipment Used	RLT Tests (Preferred Method) Resonant Column Test Torsional Ring Shear Test Cubical Triaxial Test
Calibration Issues—Repeatability and Reliability Issues	Still a problem; One study reported the use of synthetic specimens with known stiffness properties; Wide range of properties
Test Procedure Used for RLTs	T-274 was used in early studies followed by T-292 and T-294 methods; TP-46 was also used in the later studies; All studies used conditioning, followed by testing at various confining and deviatoric stresses; Stress sequence and stress ratios are different in each of these methods
Material Types	Most of the studies focused on natural subgrades; a few others studied aggregates and granular sandy soils
Specimen Preparation Methods	Most of the methods use impact compaction with standard Proctor energy efforts Others used static compaction and kneading compaction methods
Compaction Conditions	Close to optimum moisture contents; Several studies investigated variations in compaction moisture contents from dry to optimum to wet of optimum
Models to Analyze M_R Data	Bulk stress (granular materials) and deviatoric stress (cohesive soils) models are frequently used since they are the recommended models by the AASHTO procedures

performed by various DOTs to validate the previous research findings and new research to determine M_R of the local soils. In this phase, all recent literature involving the use of resilient modulus testing from different state-funded research studies using T-294 and T-307 methods are reported.

This information is synthesized in Tables 7 and 8, with Table 7 summarizing the test information, including test method followed, specimen preparation method adapted, and types of soil and aggregate materials tested. Table 8 summarizes salient findings and conclusions from the research performed by the reporting agencies. These references are listed along with the state DOTs that provided funding for the respective research.

Tables 7 and 8 present various available final research reports collected from the extensive literature review performed for this research. The research presented herein refers to the final research reports, because they contain more detailed information on the tested materials and analyses of test results.

The following general summary provides information on the resilient modulus of aggregates and subgrades that is relevant to both researchers and practitioners. Several DOTs funded research, which is summarized in the tables. Most of these studies addressed resilient properties of the subgrades encountered in various states and a few addressed aggregate and granular bases used in the respective state.

- Several new research studies from different DOTs were conducted during this phase. Though the total number of these studies is impressive, more studies are still needed for a better understanding of resilient properties of several other states. Among the state DOTs, Florida, Minnesota, Texas, Mississippi, Ohio, and New Jersey lead considerable research efforts on laboratory testing and also implemented the use of resilient properties of subgrades in their pavement design practice. Several other states including Illinois, Louisiana, and others have started implementing or are planning to implement the M_R value in their pavement design practice.
- In the case of resilient modulus studies on aggregate bases, limited research studies have been performed. Studies in this area mainly came from the states of Ohio, Texas, New Jersey, South Carolina, and Minnesota. Details on the aggregates research are presented in the later sections.

The test equipment primarily used over the last 10-plus years is RLT test apparatus. A few studies—including those by Nazarian et al. (1996), Davich et al. (2004b), and Gupta et al. (2007)—experimented with the use of bender element testing to determine the small-strain shear modulus, which was then correlated to the resilient modulus with an assumed Poisson's ratio. Figure 35 presents a typical bender element setup made of piezoelectric elements used by Davich et al. (2004b). A wave pulse generated by emitter (bender element) from one end will travel through the soil specimen and reaches the receiver (another bender element) at the other end. Based on the travel time of a shear wave and mass density of the soil specimen, the small-strain shear modulus value is determined.

TABLE 7
RESEARCH REPORTS AND PAPERS ON RESILIENT MODULUS AFTER 1996—TEST INFORMATION

Reference & Supporting DOT	Description of Research	Soil and Aggregate Types Tested	Test Procedure Followed
Nazarian et al. 1996 & Texas DOT (TxDOT)	Development of Test Method of Aggregate Bases	Four types of Granular bases including Caliche, Limestone, Gravel and Iron Ore materials were used.	RLT test equipment was used; T-294 procedure was followed; bender element setups were also evaluated.
Gandara et al. 2005 & TxDOT	Effects of Fines on Aggregate Bases	Aggregate Bases	Three confining pressures and three deviatoric stresses at each confining pressure (similar to T-307); Specimens are grouted at the ends; Internal LVDTs were used to measure both axial and radial strains; Study focused on amount of fines on M_R of Aggregates
Berg et al. (1996), Bigi and Berg (1996) & Minnesota DOT (MnDOT)	Resilient Modulus Testing of Untreated Subgrades	Two Clayey Subgrades and Two Bases with different amounts of fines	Specimens were compacted and then saturated and later subjected to freezing. Resilient modulus tests were conducted on frozen samples subjected to three different temperatures below freezing temperature. Some specimens in the triaxial cell were thawed and then subjected to resilient modulus tests. Loading pulse has 1 s of loading and 2 s of relaxation. Frozen samples were tested under 10 psi of confining and thawed samples were subjected at four different confining pressures. In all cases deviatoric stresses were varied.
Davich et al. (2004b) & MnDOT	Small strain and resilient modulus testing of granular soils	Six types of bases (granular types): Fine to well graded sands with fines	LTPP P-46 method was followed for performing resilient modulus testing whereas Bender element test was followed for performing small strain modulus tests.
Gupta et al. (2007) Minnesota DOT	Resilient Behavior of Unsaturated Subgrade Soils and Pavement Design	Four subgrade soils of different PI values	Two compaction conditions and three matric suctions were applied at each compaction condition and these suctions were 0, 22, and 50 psi; M_R tests and small strain bender element tests were conducted on all samples; Axis translation technique was used to apply the suction to the soil samples; M_R test procedure was based on NCHRP 1-28A
George and Uddin (2000) Mississippi DOT	Laboratory M_R Testing on Field Cores and Correlations Between M_R and Dynamic Cone Penetrometer and FWD Data	Several field subgrade samples at different depths and at different spacings (200 ft c/c); Sampling depth up to 5 ft to a maximum of 10 ft; Soil samples from 12 sections	AASHTO TP 46 Protocol; Resilient modulus test setup; External LVDT system; Laboratory M_R at 14 kPa of confining pressure and 35 kPa of deviatoric stress was used as the subgrade layer property
George (2004) Mississippi DOT	Prediction of Resilient Modulus from Soil Properties	Subgrade samples from 8 different County/Roads	TP-46 was followed RLT and impact compaction were used
Ooi et al. (2006) Hawaii DOT	Development of Correlations for M_R of Hawaii Subgrades	Subgrades from four locations in Hawaii	LTPP P-46 procedure (T-307) was followed for M_R testing; Three confining pressures were used as per the cohesive subgrade testing
Lee et al. (1997) Indiana DOT	Resilient Properties of Indiana Cohesive Subsoils	Soil specimens from three in-service subgrades	AASHTO T-274 method was used; Soil specimens were prepared using impact compaction method
Janoo et al. (1999) New Hampshire DOT	Resilient Modulus of New Hampshire Subgrades for Pavement Design	Five Subgrades from New Hampshire	TP-46 Procedure was used; Tests were conducted at several temperatures to reflect freezing and thawing; Average M_R from tested stresses were used as effective moduli; Kneading compaction was used for testing; Tests were conducted at optimum moisture content condition.
Maher et al. (2000) New Jersey DOT	Resilient Modulus Properties of New Jersey Subgrade Soils	Six Different Subgrade Soils from New Jersey	TP-46 method was followed; Three compaction moisture content conditions were studied

continued

TABLE 7 (*continued*)

Reference & Supporting DOT	Description of Research	Soil and Aggregate Types Tested	Test Procedure Followed
Bennert and Maher (2005) New Jersey DOT	Resilient Modulus Properties of New Jersey Aggregates	Two different aggregates of two types from three regions with different gradation types and two types of blended aggregated with recycled concrete and asphalt aggregates	AASHTO TP-46 method was used
Baus and Li (2006) South Carolina DOT	Studies on South Carolina Aggregate Bases	Seven types of aggregate bases	Static and cyclic plate load tests were conducted on different aggregate beds.
Ping et al. (2003) Florida DOT	Resilient Moduli of Subgrades from Florida	Two subgrade soils from Florida	AASHTO T-292 and T-294 methods were followed for M_R testing; LVDTs were placed both in the middle and at the ends of the soil specimen; RLT equipment was used for testing subgrades; Both vertical and horizontal LVDTs were used for monitoring vertical and lateral deformations
Ping et al. (2007) Florida DOT	Resilient Modulus of Subgrades from Florida	37 subgrade soils from different districts in Florida	AASHTO T-307 method was followed for M_R testing; Other procedures including T-292 and T-294 were used in the earlier M_R testing; RLT equipment was used for testing subgrades; Both vertical and horizontal LVDTs were used for monitoring vertical and lateral deformations
Hopkins et al. (2001) Kentucky DOT	Resilient Modulus of Kentucky Subgrade Soils	128 tests on soil samples collected from various locations in Kentucky	Specimens were molded at optimum moisture content and 95% of maximum dry density; TP-46 method was followed for the M_R testing.
Masada et al. (2004) Ohio DOT	Resilient Moduli of Ohio Subgrade Soils and Bases	Several aggregate types were researched with different types of gradations; Several subgrades from different locations in Ohio were collected and tested	TP-46 method was followed (Bases and Subgrades)
Wolfe and Butalia (2004) Ohio DOT	Resilient Moduli of Ohio Subgrade Soils	Thirteen Subgrade soil samples across the state of Ohio	Specimens were compacted at dry of optimum, optimum and wet of optimum; T-294 method was followed; external LVDT system was used; Both unsaturated (compacted) and saturated samples were tested.
Malla and Joshi (2006) New England Transportation Consortium (Connecticut, Maine, Massachusetts, New Hampshire, Vermont)	Resilient Moduli of Subgrades from New England States;	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.	AASHTO T-307 tests were conducted Tests were conducted at various compaction moisture content conditions
Titi et al. (2006) Wisconsin DOT	Determination of Resilient Moduli Properties of Typical Soils from Wisconsin	Seventeen soils from different regions in Wisconsin were tested. A-1, A-3, A-4,	AASHTO T-307 tests were conducted Tests were conducted at different moisture content conditions
Kim and Labuz (2007) Minnesota DOT	Resilient Modulus and Strength of Base Course with Recycled Bituminous Material	Different aggregates including Recycled Asphalt Pavement and natural aggregates	NCHRP 1-28A test protocol was used and laboratory specimens were prepared using gyratory compaction method.

TABLE 8
RESEARCH REPORTS AND PAPERS ON RESILIENT MODULUS AFTER 1996—FINDINGS

Reference	Resilient Moduli Range	Findings, Recommendations and Future Research
Nazarian et al. (1996) Nazarian et al. (1998) & TxDOT	Tested bases have M_R values ranged between 70 MPa to 210 MPa with Limestone exhibiting close to 300 MPa at optimum moisture content	Conditioning was eliminated and grouting was recommended at both ends of the specimen, which resulted in better repeatability of test results. Conditioning and testing sequence was modified for future testing in the state. Lateral deformations and Poisson's ratio were directly measured.
Gandara et al. (2005) TxDOT	Tested Aggregates have 25 to 100 ksi	Effects of fines on aggregate resilient properties are minimal; however, it does influence the moisture susceptibility of the aggregate fine soil mixtures. Type of fine material and its plasticity nature has major influence on permanent deformation. Tube suction tests on aggregates were used to address moisture susceptibility. The optimal fines in aggregates is between 5% and 10%. A field methodology is still needed to predict the performance of aggregates that can complete laboratory tests.
Berg et al. (1996) MnDOT	Lower moduli (less than 1 ksi) were reported, which was attributed to calibration error. With an inducement of freezing, the moduli of subgrades increased to 1000 ksi. For unbound bases, the M_R was 10000 ksi at high freezing conditions.	Both unbound base and subgrades exhibited a 2 to 3 order increase in resilient moduli due to freezing. M_R decreased with an increase in saturation. M_R of all soils are stress dependent. Different regression expressions are presented. Test procedures are different from AASHTO recommended procedures. In few tests, calibration errors were reported.
Davich et al. (2004b) MnDOT	Resilient moduli of bases varied from 60 MPa to 800 MPa based on confining and deviatoric stresses applied.	M_R increased with a decrease in moisture content. Hyperbolic model using small strain modulus and shear strength properties are used to predict resilient modulus. Poor bonding and uneven specimen ends resulted in the variation of the three LVDT measurements. Field measurements of small strains can be used to estimate resilient moduli needed for the pavement design. More studies are needed to validate the procedures established in this research.
Gupta et al. (2007) MnDOT	Resilient moduli based on external displacement measurements varied between 10 and 70 MPa and the same varied between 10 and 200 MPa when internal displacement system was used.	An increase in matric suction resulted in considerable increase in M_R value. A linear semi-logarithmic relationship between resilient modulus, M_R and matric suction was developed. Internal measurements always yielded higher M_R values, which are 1.7 to 3 times that of M_R values based on external measurements. Bender element data measured from unconfined compacted subgrades showed a correlation with the M_R values measured from internal measurements. Soil water characteristic curves of all four soils were developed to determine the moisture content and suction relationships. Model formulated by Oloo and Fredlund (1998) was used to analyze the M_R -Suction data.
George and Uddin (2000) Mississippi DOT	M_R values of subgrades at 14 kPa confining pressure ranged from 30 MPa to 270 MPa, with higher values being measured for upper layer samples.	Sample disturbance due to pushing of the Shelby tube resulted in higher M_R values for the top layer. Laboratory M_R varied considerably along the test section than along the depth of the section. Moisture content of the sample showed considerable influence on $M_{R.}$
George (2004) MSDOT	Resilient moduli (M_R) varied between 50 and 115 MPa.	Trends of M_R values agree with those reported in the literature.
Ooi et al. (2006) Hawaii DOT	M_R values of subgrades ranged from 10 ksi to 35 ksi for various silty subgrades and this range is dependent on confining pressures and deviatoric stressed applied in a test.	An increase in deviatoric stress resulted in a decrease in moduli of subgrades. High PI silty material exhibited lower moduli than low PI silty soils. Excessive drying of soil to meet the compaction moisture contents (soils sampled from the field at high moisture levels) may compromise the resilient properties.
Lee et al. (1997) Indiana DOT	Most M_R results varied between 30 and 80 MPa	M_R is correlated with the stress at 1% axial strain of unconfined compression strength test and this correlation did not show the dependency on compaction conditions. This relationship is valid for other cohesive soil types.

continued

TABLE 8 (*continued*)

Reference	Resilient Moduli Range	Findings, Recommendations and Future Research
Janoo et al. (1999, 2004) New Hampshire DOT	M_R results of subgrades varied from 5 ksi to 2646 ksi based on the test temperature condition	Design moduli were determined by averaging moduli measured at different confining pressures. Poisson's ratio values measured were different from those used for these types of materials and this variation was attributed to conglomeration of particles. Corrections for effective moduli are based on subgrade temperature conditions, not based on air temperatures. All test results reported are based on those compacted at optimum moisture content condition and hence moisture and density related correction is needed when the moduli values at other compaction conditions are needed.
Maher et al. (2000) Maher et al. (1996) New Jersey DOT	Resilient moduli of soils varied between 2 to 36 ksi and this variation is dependent on soil type and moisture content condition.	Granular soils exhibit strain hardening as the M_R values increased with deviatoric load applications. Cohesive subgrades showed strain softening with a decrease in M_R with deviatoric loading. Moisture content has a major effect on the moduli of both soils.
Bennert and Maher (2005) New Jersey DOT	M_R values of natural aggregates varied from 13 to 23 ksi whereas the same for blended aggregates varied from 20 to 40 ksi at stress conditions close to those expected under pavements	Addition of recycled aggregates enhanced the resilient properties. Recycled asphalt aggregates blending has more profound effect on the M_R values than recycled concrete aggregates. As the gradation of aggregates become finer, the resilient properties decrease.
Baus and Li (2006) South Carolina DOT	M_R values of aggregate bases from static plate load tests varied from 14 to 77 ksi.	A structural coefficient of 0.18 is recommended for aggregate bases in the pavement design. Relaxation of coarse gradation did show a positive influence in enhancing the resilient modulus. Reevaluation of structural coefficients is needed by performing field tests.
Ping et al. (2003) Florida DOT	M_R values of sandy soil varied from 90 to 340 MPa based on the confining and deviatoric stresses applied during the testing and the same for cohesive soil varied from 60 to 170 MPa.	Adjustment factors are introduced to convert M_R from one test procedure to another test procedure and one measurement system (end system) to another (middle system).
Ping et al. (2007) Florida DOT	The M_R values of Florida subgrade soils ranged from 7 ksi to 26 ksi, with an average value of 14 ksi	Two databases of moduli were developed, one with comprehensive moduli data and the other with integration and analysis functions. Physical properties such as density and moisture content and LBR influence the M_R magnitudes of A-2-4 soils than A-3 soils. An increase in clay and fines content also influences the M_R values. Gradation properties such as uniformity coefficient and coefficient of curvature have less influence on the $M_{R.}$ Several prediction models were developed for M_R results. More soil information from previous M_R tested soils will further enhances the model development.
Hopkins et al. (2001) Kentucky DOT	Compacted soil specimens exhibited M_R values ranging from 20 ksi to 28 ksi at a low confining pressure of 2 psi.	Unsoaked soil specimens performed well under resilient modulus testing whereas soaked specimens experienced large deformations, which resulted in bulging in some cases. Three models were developed for the analysis of the present results. Need for a resilient modulus test to perform on a nearly saturated soil specimen Acceptance criteria for M_R testing should be developed.
Masada et al. 2004 Ohio DOT	M_R of bases varied from 3 ksi to 65 ksi, and average values of the aggregate bases varied from 9 to 42 ksi. M_R of subgrades varied from 12 to 24 ksi for A-4 soils; 3 to 23 ksi for A-6 soils; and 4.5 to 25 ksi for A-6 soils.	This research summarized various research studies conducted in the state Ohio and several lab and field tests were conducted on both unbound bases and subgrades. Moduli results from these studies are summarized.

continued

TABLE 8 (*continued*)

Reference	Resilient Moduli Range	Findings, Recommendations and Future Research
Wolfe and Butalia (2004) Ohio DOT	M_R values of subgrades varied from 10 MPa to 120 MPa and lower values were measured when tests were conducted on wet of optimum soil samples	An increase in moisture content resulted in the reduction of resilient properties. In the case of A-4 soils, saturation resulted in the reduction of M_R by 8% to 88% where as the same for A-6 and A-7-6 soils varied from 50% to 87% and 44% to 82%, respectively. Field instrumentation with tensiometers and moisture probes are recommended for better understanding moisture flow patterns in subgrades, which in turn influences M_R results.
Malla and Joshi (2006) New England Transportation Consortium (Connecticut, Maine, Massachusetts, New Hampshire, Vermont)	M_R of tested soils varied from 30 to 160 MPa;	For coarser soils, M_R increased with deviatoric axial stress and for cohesive soils, M_R decreased with deviatoric stress. Several prediction models were also developed for these soils.
Titi et al. (2006) Wisconsin DOT	M_R of tested plastic coarse soils varied from 15 to 160 MPa; M_R of non-plastic coarse soils varied from 20 to 140 MPa; M_R of tested subgrade soils varied from 10 to 160 MPa;	All tests showed good repeatability. Test database was used to develop correlations of Level 3 type. Trends with respect to confining and deviatoric stress are in agreement with those reported in the literature.
Kim and Labuz (2007) Minnesota DOT	Four percents of RAPs were mixed with natural aggregates and resilient moduli tests on aggregates showed that the M_R varied between 125 and 700 MPa.	M_R increased with an increase in confining pressure and deviatoric stress has no effect on the moduli magnitudes. Increase in RAP amount resulted in an increase of moduli.

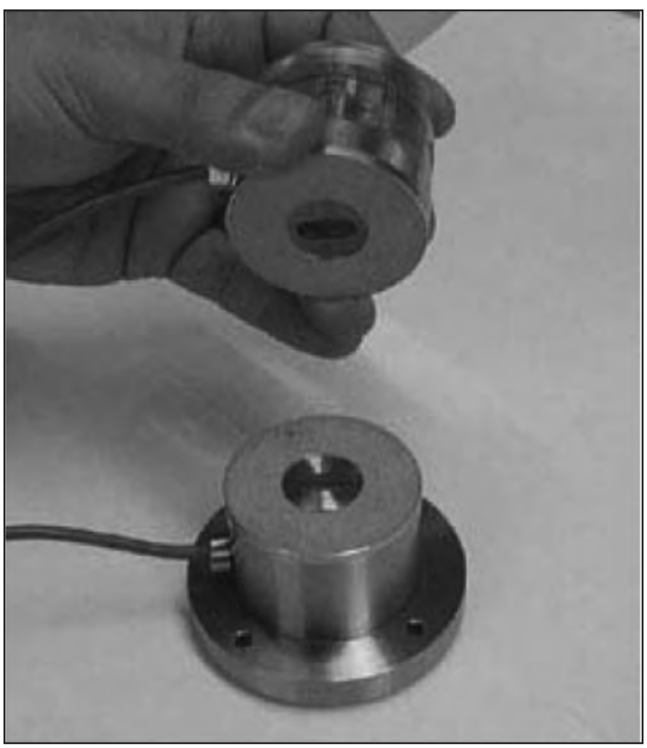


FIGURE 35 Bender element setup used by Davich et al. 2004b.

The small-strain shear modulus (G_{max}) is typically correlated with resilient modulus (M_R or E_{max}) at low strains using the following relationship:

$$M_R = 2 \times G_{max} \times (1+\mu) \tag{4}$$

where μ is Poisson's ratio. Figure 36 presents a typical comparison of M_R from RLT test results and E_{max} from bender element tests. Though the bender element method provided a similar trend as that of resilient properties from RLT, they are not the same. This is because of the variations

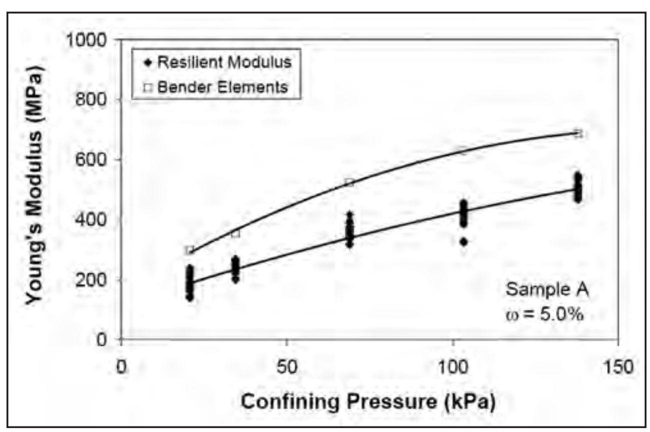


FIGURE 36 Comparisons of elastic moduli from RLT and bender element tests (Davich et al. 2004b).

in the strains at which these properties are measured. Other limitations include the difficultly interpreting travel time periods and necessity for skilled personnel and persons with considerable experience to interpret these results.

- Regarding the test procedures used, the majority of the research studies used T-294, T-307, and TP-46 methods. All these methods include conditioning and testing cycles with different sets of confining and deviatoric stresses for both cohesive and granular soil types. Constant modification of test methods for M_R measurements also contributed to a certain lack of interest in the resilient modulus test procedures as indicated by one of the survey respondents. The newer test methodologies such as T-307 are considered as refined test procedures for determining the M_R values. However, there is no good one-to-one correlation between moduli measured from one method to other methods unless a few correction factors are applied, as suggested by Mohammad et al. (1994) and Ping et al. (2003).
- The majority of the research studies used either external or internal measurements, which showed certain variations in the M_R measurements (Ping et al. 2003; Ping and Ling 2007). Figure 37 presents a typical comparison of M_R measurements from end and middle measurements. These studies confirm the earlier findings reported by Mohammad et al. (1994). Though internal measurements tend to measure displacements that are free from system compliance errors, adaptation of this method in a routine test can take considerable time. Hence, external LVDT systems are recommended for the M_R measurements in the recent AASHTO T-307 method.
- Another important source of error is the need to grout the ends of the soil specimens, because irregular surfaces result in erroneous resilient deformation measurements. Gandara et al. (2005) recommended the use of grout-ended specimens for modulus testing. Figure 38 shows photographs of grouting being performed at the ends of specimens. Such procedure is highly recommended for stiffer materials, such as unbound aggregates, to achieve reliable measurements of M_R values. Figure 39 presents typical resilient properties of grouted granular specimens tested by Gandara et al. (2005).
- Soil specimen conditioning before M_R testing is not unique and several research studies adapted different approaches for the testing based on their experience with the moisture information of the local subgrades. The majority of the studies reported that the testing is being performed on the soil specimens as compacted. Most of these soil samples are in unsaturated conditions. A few studies reported the use of soaked soil specimens (Hopkins et al. 2004; Masada et al. 2004; Wolfe and Butalia 2004) by saturating the compacted soil specimen. Figure 40 presents a typical resilient modulus measurement of a clayey subgrade at different moisture content and related saturation conditions. A decrease of close to 70 MPa was observed in the moduli value when the clayey subgrade was subjected to full saturation from the dry compaction state. Most of the studies reported over the last 10 years also noted the importance of moisture content and moisture conditioning on the resilient moduli properties.

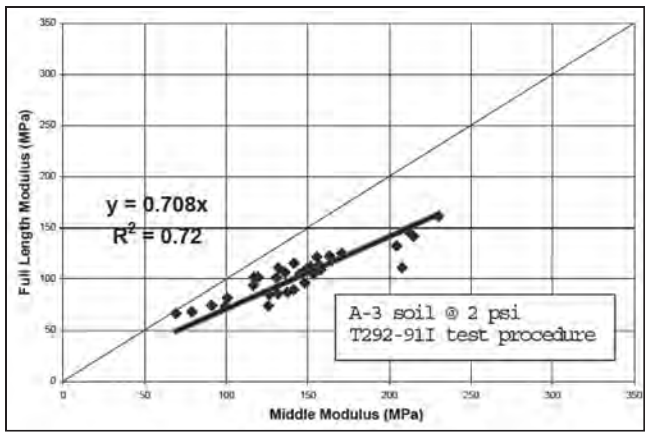


FIGURE 37 M_R measured from LVDTs placed in the middle versus ends of A-3 Soil Specimen (Ping et al. 2003).

FIGURE 38 (*left*) Grout used for specimen ends; (*right*) Leveling measurements on the top cap (Gandara et al. 2005).

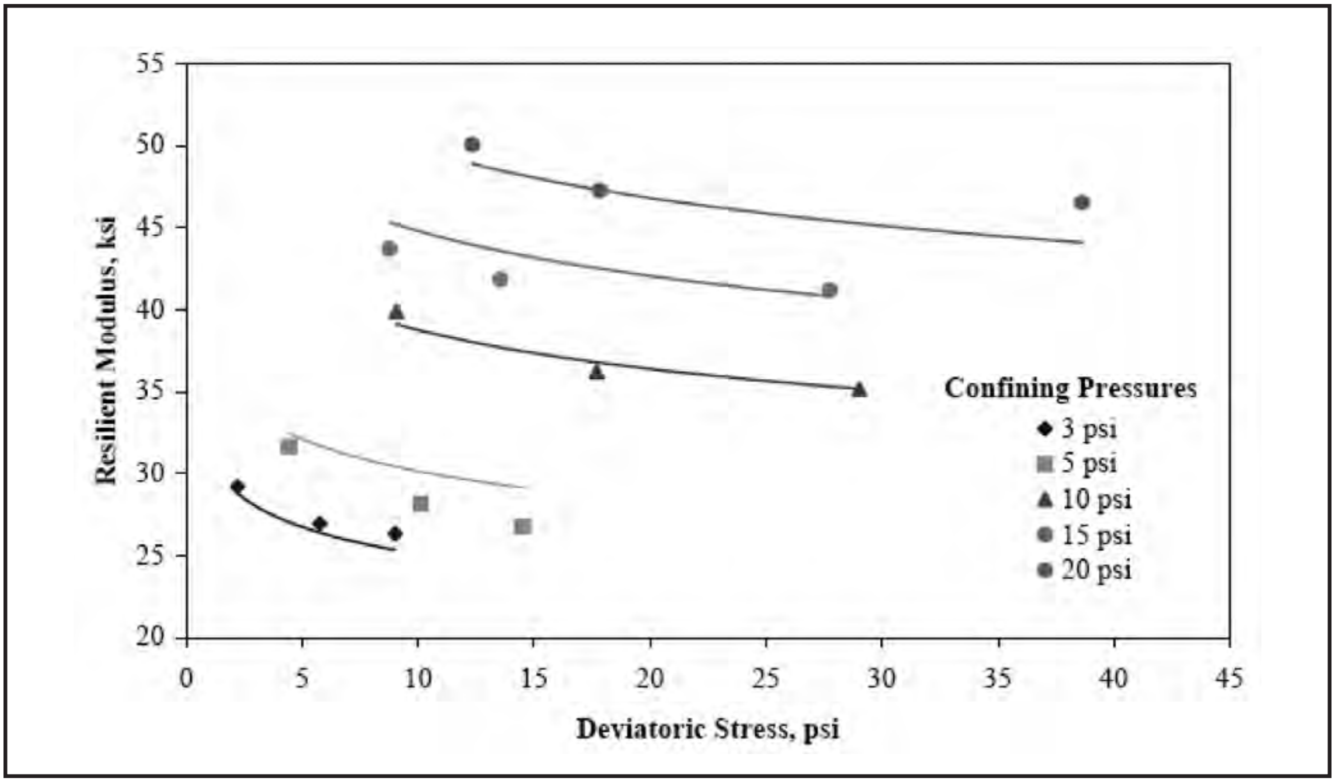


FIGURE 39 Typical resilient moduli of granular specimen grouted at the ends (Gandara et al. 2005).

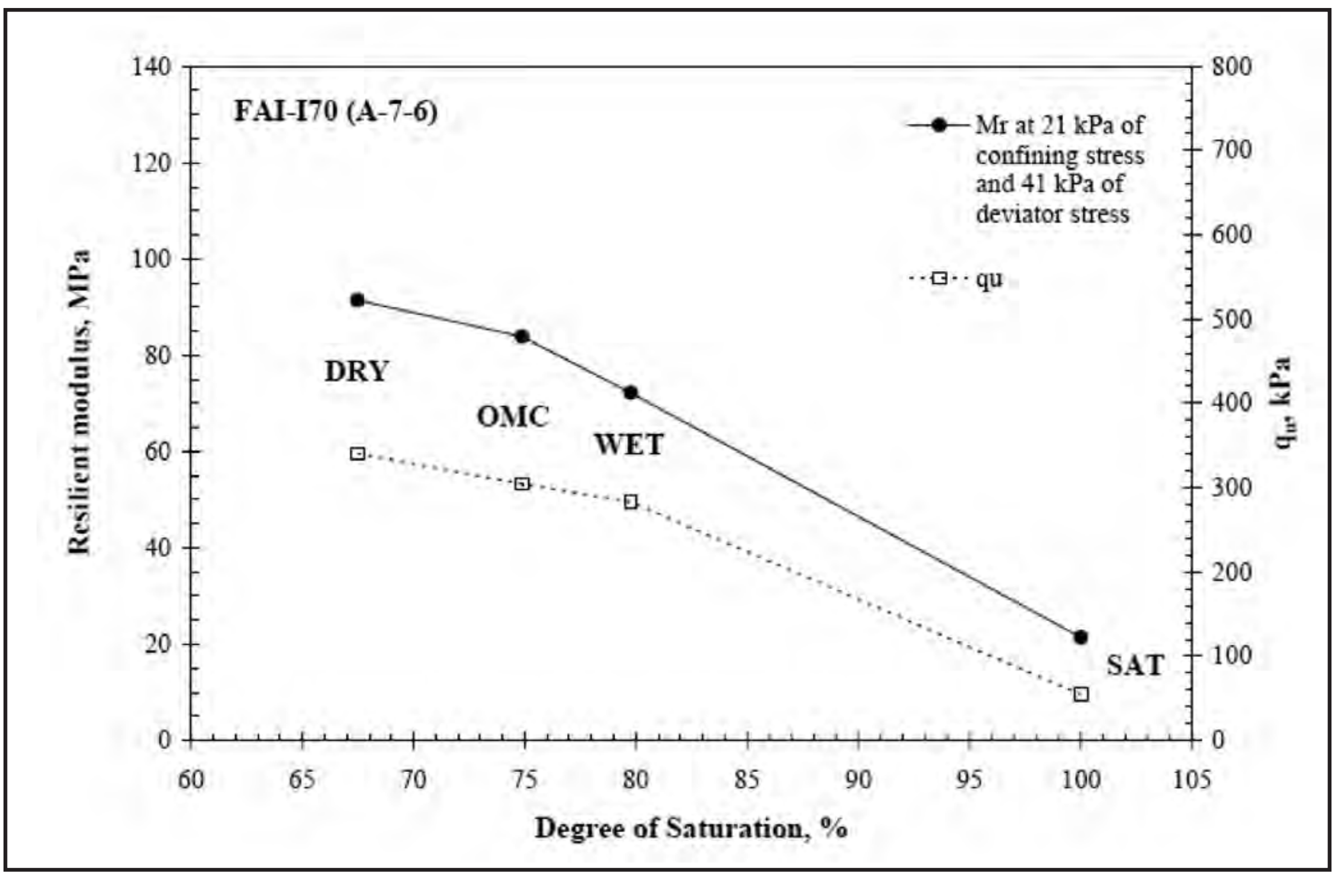


FIGURE 40 Resilient moduli of subgrade specimens at different saturation conditions (Wolfe and Butalia 2004).

Hopkins et al. (2004) noted that the saturation of the soil specimen represents the subgrade conditions in the state of Kentucky. This study also noted that the current procedures, including T-307 and TP-46, do not specify a procedure for performing tests on soaked specimens and recommends this as an important future research need.

- In the case of soils tested in cold regions, Berg et al. (1996) described resilient properties of subgrades subjected to different freezing temperatures and thawing conditions in the laboratory environment. Specimens were compacted, saturated, and then subjected to freezing at a certain temperature. The frozen samples were then subjected to M_R testing, followed by a thawing process in the laboratory setup upon which it was subjected to additional resilient modulus testing. Figure 41 presents a typical resilient modulus response of subgrades subjected to different freezing conditions.

Janoo et al. (1999) also reported the freezing and thawing effects on the resilient properties of New Hampshire subgrades for "unfrozen to frozen" conditions followed by "frozen to thaw" conditions. Figure 42 presents typical test results for a silty sand subgrade. Both studies reported two to

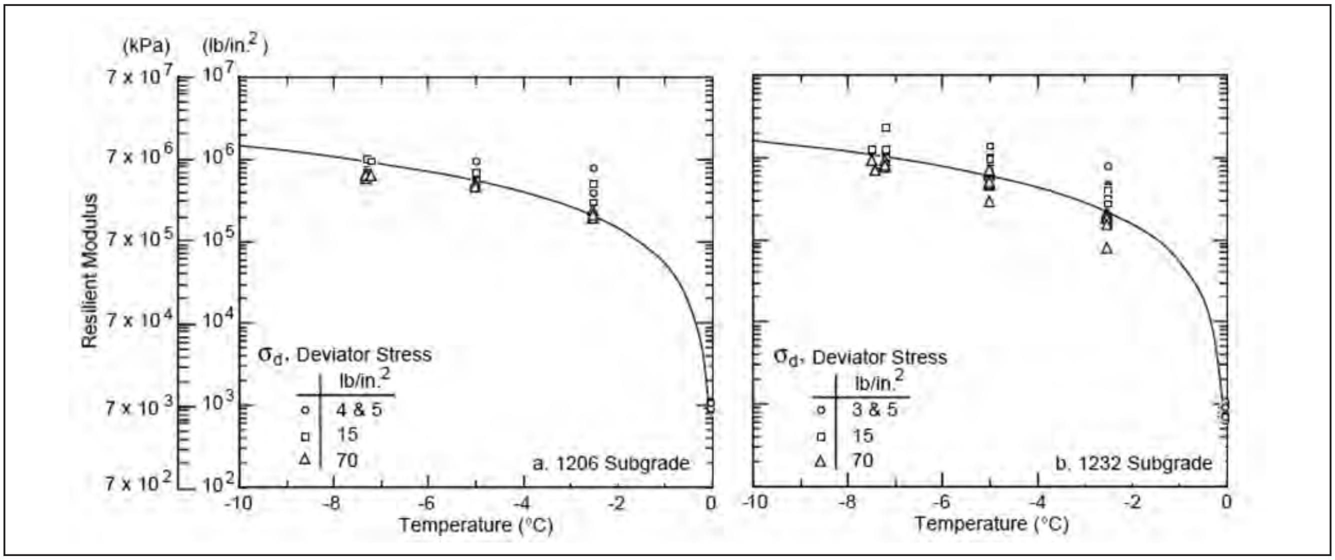


FIGURE 41 Resilient moduli of subgrade specimens subjected to different freezing temperatures (Berg et al. 1996).

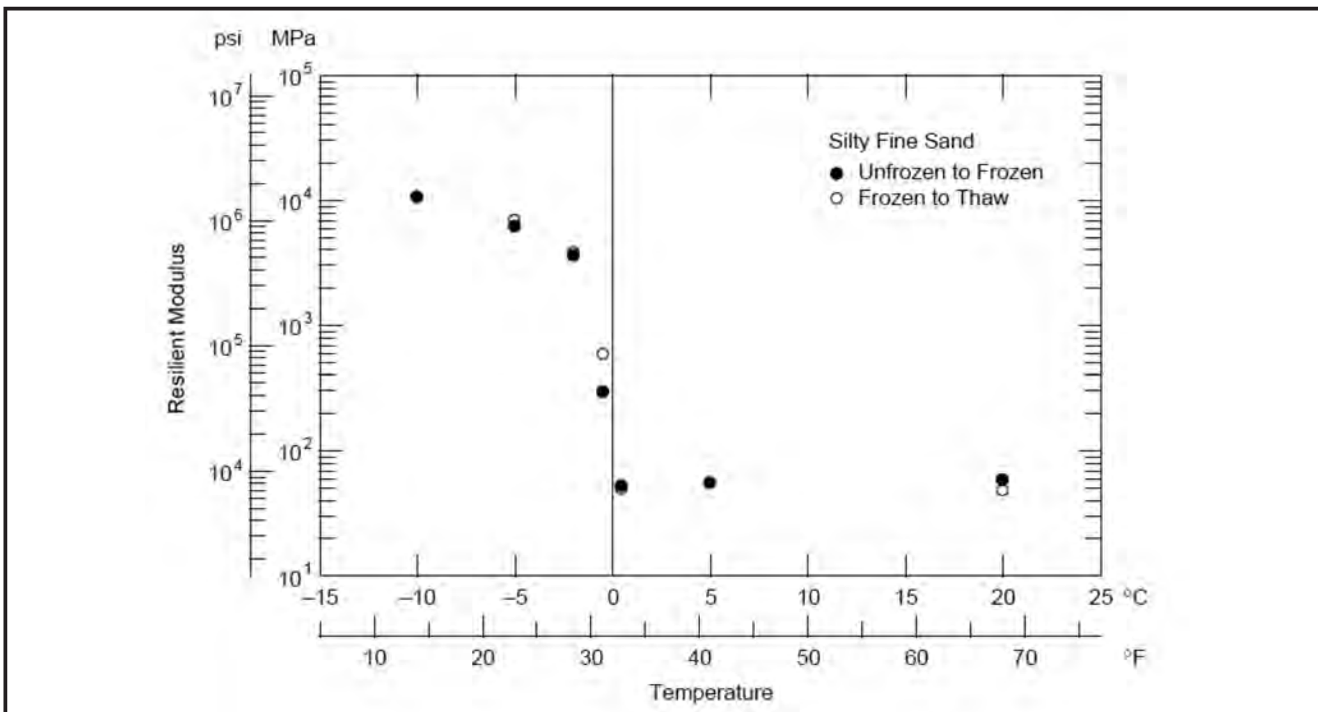


FIGURE 42 Resilient moduli of silty fine sand specimens subjected to different freezing temperatures (Janoo et al. 1999).

three orders of decrease in the resilient properties as a result of freezing and thawing effects. This signifies the need to determine the effective roadbed modulus in cold regions by accounting for freezing and thawing effects.

On a different, but related topic, Ooi et al. (2006) recommended against drying of subgrades because drying may alter the resilient responses of the soil specimen as it exhibits different moisture-related affinity than the one without drying conditions.

- Recent studies performed by Wolfe and Butalia (2004); Edil et al. (2006); and Gupta et al. (2007) focused on the unsaturated soil principles and its implications to the resilient modulus property and the related mechanistic pavement design. The majority of the subgrades are expected to be in unsaturated conditions for most of their design life and hence the suction of subgrades in the unsaturated state plays an important role on both resilient properties and pavement design principles.

Wolfe and Butalia (2004) focused on the suction measurements in the field using tensiometers and then addressed the moisture content fluctuations in both base or subbase and subgrade environment. These measurements raised some concerns about the assumptions of using drainable conditions in the bases. The Edil et al. (2006) and Gupta et al. (2007) studies were conducted for the Minnesota DOT (MnDOT), and they addressed the need to incorporate soil suction effects into the M_R modeling. Edil et al. (2006) described an M_R framework suggested by Oloo and Fredlund (1998) that accounts for soil suction effects. Figure 43 presents the effects of matric suction on the resilient moduli of subgrade soils tested at various suction conditions. An increase in suction showed an increase in M_R value of the soil because an increase in suction is always associated with dry conditions in the soil specimens.

This research is an important step in the better understanding of resilient properties of unsaturated soils. More such understanding will help in better mechanistic design of pavements built on subgrades in regions where full satu-

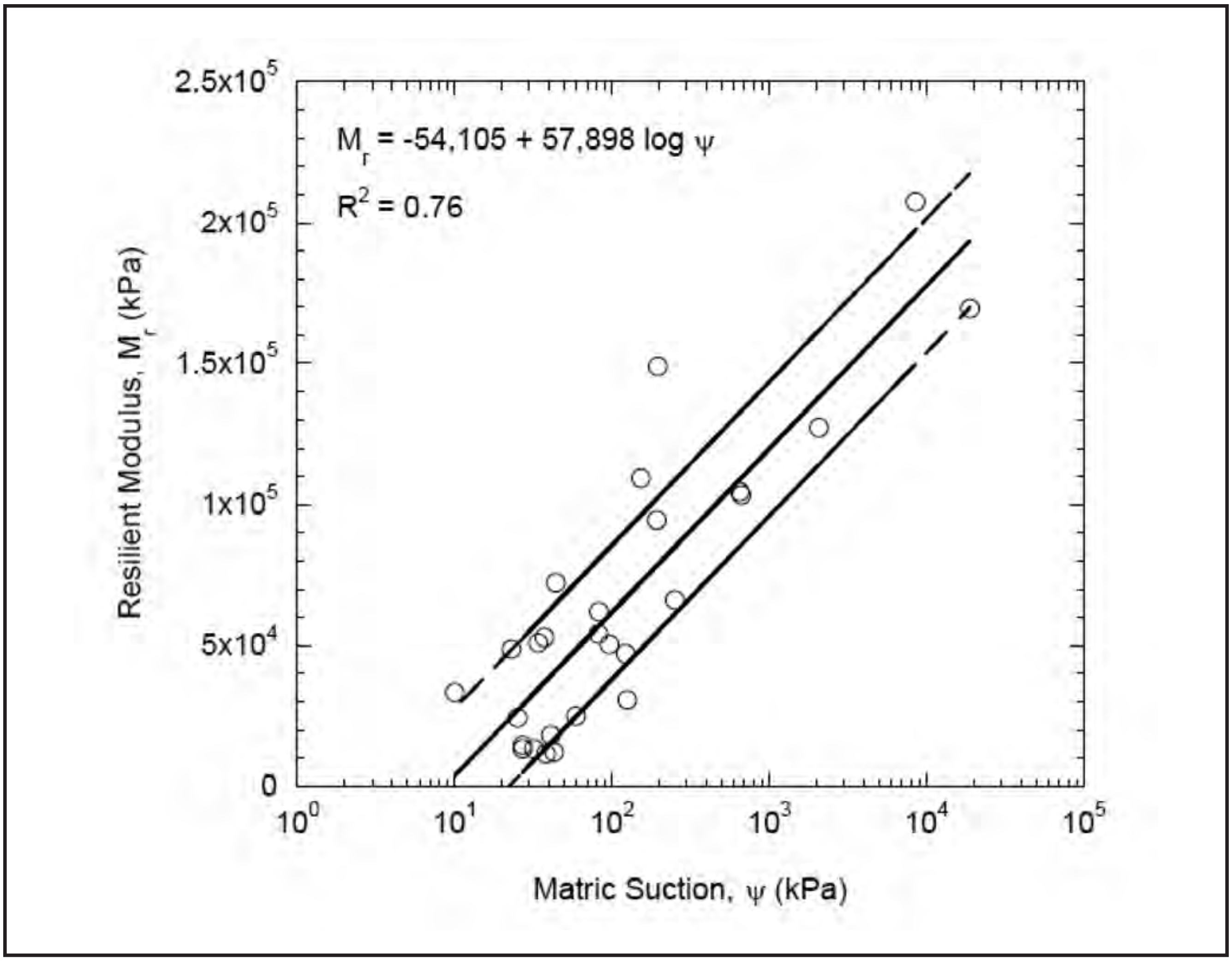


FIGURE 43 Effect of matric suction on resilient modulus (Edil et al. 2006).

ration conditions seldom occur. Several regions in Western and Midwestern U.S. states belong to this category owing to arid and desert-like conditions.

- Regarding the sequence of testing and magnitudes of confining and deviatoric stresses applied, the majority of the studies followed those mentioned by the standard protocols. A few deviated from them by using the stresses expected in the field as per the traffic loading conditions.
- Several soil-related variables including soil type, Atterberg limits, group index properties, and compaction conditions influence the resilient property measurements. These observations are in agreement with the past M_R studies performed before 1996. Studies conducted by Maher et al. (2000), Hopkins et al. (2001), Masada et al. (2004), Malla and Joshi (2006), and Ping and Ling (2007) documented resilient properties of a variety of subgrade soils. Though no overlap was noted in the test results reported by these studies, the M_R values of cohesive soils ranged from 2 to 42 ksi and the M_R values of granular bases and subbases as well as unbound aggregates ranged from 10 to 45 ksi. Another study conducted by Kim and Labuz (2007) reported resilient moduli of different aggregates containing different amounts of reclaimed asphalt pavement (RAP) aggregates. An increase in the RAP amount resulted in an increase in moduli values. Kim and Labuz (2007) reported that the in situ aggregate blend from full-depth reclamation yielded moduli similar to blend containing 50% of natural and 50% RAP aggregates.
- Selection of design moduli from the laboratory tests is arbitrary and no recommended procedures are available. In a few studies, the average modulus over a set of confining pressures is calculated and used as a design modulus for a given test conducted on a certain moisture condition. George and Uddin (2000) have used a modulus value measured at a confining pressure of 14 kPa under a deviatoric stress of 35 kPa as a design modulus. Hopkins et al. (2004) performed a comprehensive stress analysis of a subgrade subjected to traffic loading and then determined both confining and deviatoric stress conditions that are representative of subgrades. A modulus measured from the laboratory data corresponding to the stresses determined from layered elastic analysis is used as the design modulus.

Overall, the information compiled over the last 10-plus years during the third phase of research showed considerable advances on the resilient modulus testing of various subgrades and unbound aggregates, which lead to the development of a large M_R database for a better interpretation of resilient properties for mechanistic pavement design. The LTPP database, for example, includes M_R information of different soils and aggregates tested across the United States.

Several other studies researched information in the LTPP database related to resilient moduli characteristics of bases and subgrades (Alavi et al. 1997; Von Quintus and Killingsworth 1998; Yau and Von Quintus 2002; Richter 2006). Yau and Von Quintus (2002) studied various test variables, including the test and sampling procedures on the measured resilient moduli. M_R data from LTPP were acquired, screened, and then analyzed. Only M_R results of base and subbase aggregate layers and subgrade soils were studied.

The Yau and Von Quintus study (2002) aimed at developing relationships between resilient modulus and physical properties of the unbound materials and soils. Nonlinear regression equations were developed for each base and soil type to determine the resilient modulus at a specific stress state using the physical properties of the base materials and soils. The models developed predict the resilient properties reasonably; however, the authors concluded that a bias is present in the calculated values. A final important outcome of this research is the need for additional test results to improve or confirm these models. More discussion on the models from the LTPP database is covered in the later sections.

Richter (2006) presented an overview of several factors that influence the moduli of unbound materials from nonfrozen grounds (see Table 9). This report specifically focused on seasonal moisture content and temperature fluctuations as well as other related factors and how they influenced the backcalculated M_R properties.

INTERNATIONAL PERSPECTIVES

In this section, the M_R research work performed outside the United States is briefly summarized. This task focused mainly on the resilient moduli studies used for flexible pavement design. This investigation highlights other countries' research that could be useful for the present synthesis.

Australia, New Zealand, and the United Kingdom have been actively involved in the M_R research for several years. Research reports from the United Kingdom highlight the moduli studies conducted on both aggregate and recycled pavement bases as well as subgrades (Brown 1974, 1996; Dawson et al. 1996; Fleming et al. 1998; Lekarp and Dawson 1998; Frost et al. 2004). Similar research reports and pavement design guides from Australia and New Zealand describe efforts in the characterization of unbound aggregates in pavement design (Nataatamadja 1992, 1993; Nataatmadja and Tan 2001; Vuong 2001; Vuong and Hazell 2003; Byers et al. 2004).

In South Africa, the pavement design practice also relies on the resilient moduli properties, and both laboratory- and

TABLE 9
EFFECTS OF SOIL AND BASE MATERIAL PROPERTIES ON RESILIENT MODULI VALUES (RICHTER 2006)

Independent Variable	Base/Subbase Material							Soils			
	303, Crushed Stone	304, Crushed Gravel	302, Uncrushed Gravel	306, Sand	308, Coarse-Grained Soil-Aggr. Mixture	307, Fine-Grained Soil-Aggr. Mixture	309, Fine-Grained Soil	Gravel	Sand	Silt	Clay
Percent passing 3/8-in sieve, $P_{3/8}$	√	√		√	√	√		√	√		
Percent passing No. 4 sieve, P_4					√	√			√		√
Percent passing No. 40 sieve, P_{40}	√	√		√	√		√				√
Percent passing No. 200 sieve, P_{200}			√		√	√			√		√
Percent Clay, %Clay								√	√	√	√
Percent Silt, %Silt									√	√	√
Liquid Limit, LL	√	√		√		√		√	√		√
Plasticity Index, PI		√		√	√		√	√		√	
Water content of test specimen, W_s		√	√		√			√	√	√	√
Dry density of test specimen, γ_s		√	√		√	√			√		√
Optimum water content, W_{opt}	√	√	√		√	√			√		√
Maximum dry unit weight, γ_{max}	√	√	√	√	√	√			√		√
Number of M_R Tests	109	49	81	66	187	32	92	122	509	108	512

1 in = 25.4 mm

field-based methods have been practiced for the determination of M_R properties (Theyse et al. 1996). An overview of the pavement design methodology by Theyse et al. (1996) noted that the design methodology was developed based on decades of pavement research in South Africa. This mechanistic design was reported to be well calibrated against the experience of road engineers from various agencies in South Africa.

Several other countries including European and Asian countries reported the use of moduli for analytical pavement design (Leksø et al. 2002). The majority follow AASHTO test methods for moduli determination. The methods of pavement design practices in these countries is still not well known or not widely reported. Nevertheless, several countries have already practiced or are in the process of implementing mechanistic flexible pavement design using resilient moduli properties.

SUMMARY

This chapter describes laboratory tests practiced and studied in various U.S.-based investigations to determine the resilient or stiffness properties of unbound bases and subgrades. Laboratory studies are described in three sections, each covering various years of research investigations performed with the support of different state DOTs. In each section, the salient findings from the presented literature review are summarized.

CHAPTER FOUR

FIELD METHODS FOR MATERIAL STIFFNESS MEASUREMENT

FIELD TESTS

Several in situ methods have been used to predict or interpret the resilient moduli or stiffness of unbound bases and subgrades (pavement layers). These methods can be grouped into two categories: nondestructive methods and intrusive methods. The following sections present a brief review on these methods.

Nondestructive Methods

Nondestructive methods for determining the stiffness (*E*) are based on several principles, including geophysical principles. Some of the methods involve the measurement of deflections of pavement sections subjected to impulse loads and then employ backcalculation routines to estimate the stiffness properties of pavement layers such that the predicted deflections match with the measured deflections. The following sections briefly review some of the nondestructive methods and then provide a synthesis of the available practices adopted by the states employing these devices.

Dynaflect

Dynaflect is a light-weight two-wheel trailer equipped with an automated data acquisition and control system. The pavement surface is loaded using two counter-rotating eccentric steel weights, which rotate at a constant frequency of eight cycles per second (8 Hz). This movement generates dynamic loads of approximately ±500 lb (227 kg) in magnitude (Choubane and McNamara 2000). The total load applied to a pavement system is a combination of the static weight of the trailer and the dynamic loads generated by the rotating weights. The deflections of the pavement system are measured by five geophones suspended from the trailer and placed at 1 ft intervals. Deflection data monitored during the loading is then analyzed using both theoretical and empirical formulations to determine the modulus of subgrade and base layers.

Falling Weight Deflectometer

FWD applies an impulse load on the pavement surface by dropping a weight mass from a specified height and then measures the corresponding deflections from a series of geophones placed over the pavement surface. Deflection profiles under different impulse loads will be measured and analyzed with different theoretical models of distinct constitutive behaviors to determine the modulus of various layers in the pavement system. The analysis uses backcalculation routines that assume a different modulus for each layer of the pavement and then use a specific algorithm to predict the deflections of the pavement surface. If the predicted deflection pattern and magnitudes match with the measured deflections, then the assumed moduli are reported as the moduli of the pavement layers.

GeoGauge

GeoGauge is a portable instrument that can provide stiffness properties of subgrade and base layers. Stiffness properties are measured by inducing small displacements to the soil on a loaded region using a harmonic oscillator operating over a frequency of 100 to 196 Hz. Sensors of the GeoGauge will measure both force and displacement, which in turn will be used to measure soil stiffness properties. Stiffness property is determined by measuring and averaging stiffness values at 25 frequencies. Figure 44 presents a schematic of the cross-section of the GeoGauge. Detailed description and operation details can be found in Lenke et al. (2001).

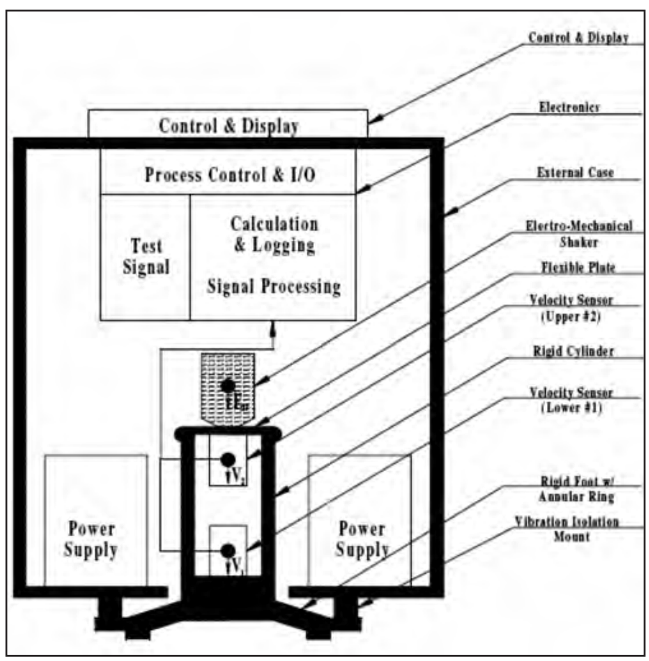


FIGURE 44 Schematic of GeoGauge (Lenke et al. 2001).

Seismic Pavement Analyzer

The seismic pavement analyzer (SPA) is an instrument designed and constructed to monitor construction and the deterioration in the pavement layers (Nazarian et al. 1995, 2003, 2005). The SPA determines the Young's modulus of elasticity and shear modulus of pavement layers. The portable SPA (PSPA) is typically used for pavement material properties and the dirt SPA (DSPA) is used on constructed subgrades and bases to determine the layer properties. The SPA lowers transducers and sources to the pavement and digitally records surface deformations induced by a large hammer that generates low-frequency vibrations and by a small hammer that generates high-frequency vibrations (Nazarian et al. 1995, 2003, 2005). The test at a site is relatively quick one, taking 1 minute. A schematic of the test setup can be seen in Figure 45.

A spectral analysis of surface waves is performed in the field to determine the shear wave velocities and the related moduli of layers. The moduli determined from SPA tests are at small-strain levels and they are different from the resilient modulus values that are representative of medium- to high-strain levels (Nazarian et al. 1995). In general, the moduli or stiffness measured from nondestructive tests are representative of stiffness properties at small- to medium-strain levels, whereas the M_R is representative of stiffness at small- to high-strain levels depending on the strength of the soil specimen tested (Nazarian et al. 1995). These variations in strains contribute to the differences in the field moduli and laboratory-measured moduli.

Light Falling Weight or Portable Deflectometers

Among nondestructive assessment of pavement layers, portable deflectometer–type devices have been receiving considerable interest by several DOT agencies. Similar to the full-scale FWD-type tools, these devices utilize both dynamic force and velocity measurements by means of different modes such as transducers and accelerometers. These measurements are then converted to elastic stiffness of the base or subgrade system, which is equivalent to homogeneous Young's modulus of the granular base and subgrade layers, using equations that assume underlying layers as homogeneous elastic half-space.

Factors that influence the stiffness estimation of field devices also influence these methods, and hence some variations in moduli values are expected with the same group of devices that operate on different principles. A few of these Light Falling Weight or Portable Deflectometers, which are abbreviated as LFWD, LFD, PFWD, or LWD in the literature, are described in the following sections. For simplicity's sake, these devices are abbreviated as LWDs in the remainder of the synthesis report.

PRIMA 100 Equipment. The PRIMA 100 equipment is a portable LWD, which can be used to measure in situ material modulus. Figure 46 shows the equipment.

The device consists of a handheld computer, mass, guide rod, load cell, velocity transducer, and a 200-mm diameter plate. A mass freely falls from a known height along the

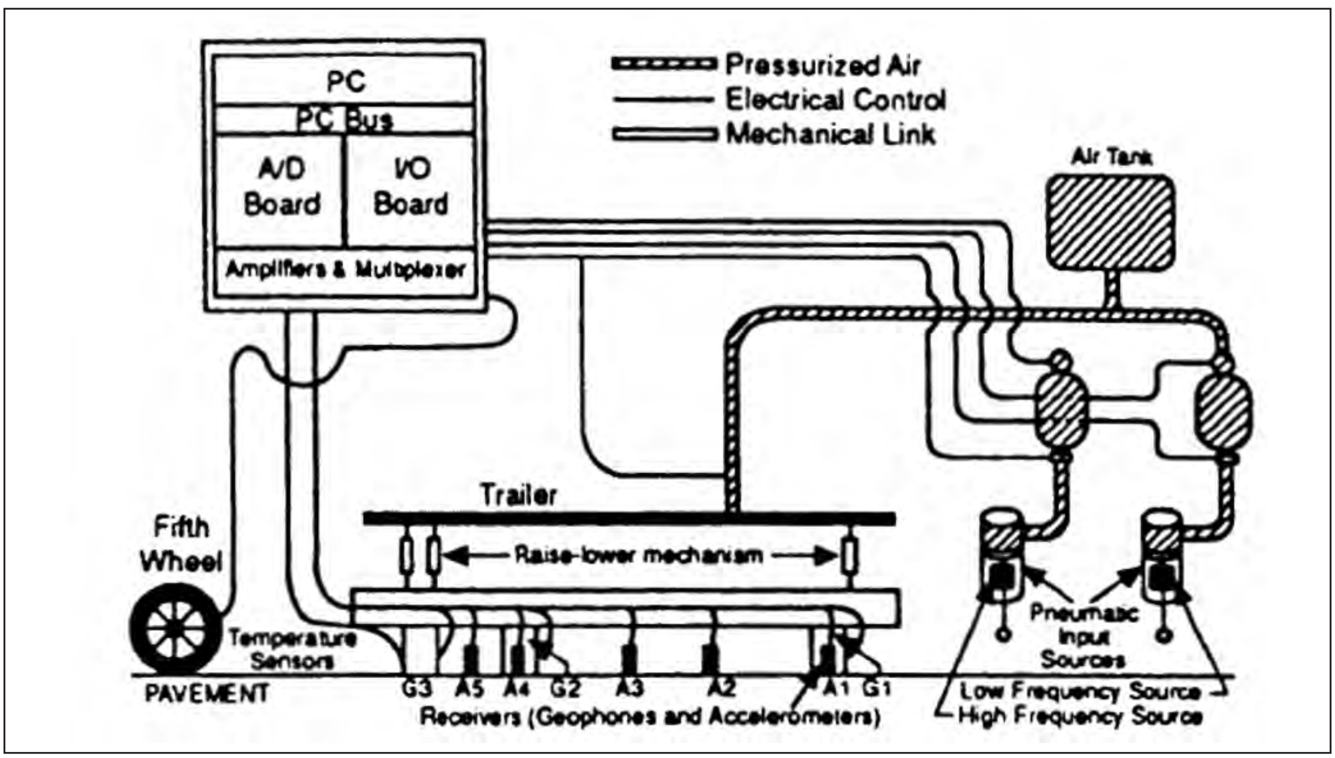


FIGURE 45 Schematic of SPA (Nazarian et al. 1995).

FIGURE 46 Prima 100 (LWD) (Petersen and Peterson 2006).

guide rod shown in Figure 46, and it impacts a load cell at the lower end of the rod. A velocity transducer, which protrudes through the center of the plate, measures velocity. Velocity is integrated with respect to time to determine displacement, and a time history of the impact load and displacement are then displayed (Petersen and Peterson 2006; Petersen et al. 2007). This LWD weighs about 40 lb with approximately half of its weight being in the falling mass (22 lb). The PRIMA 100 can be adjusted such that the height of fall can be varied resulting in the possibility of measuring modulus at different stress states (Petersen and Peterson 2006).

The following steps described by Petersen and Peterson (2006) explain the test procedure: (1) locate a smooth and level spot for the test; (2) assemble LWD and place the LWD on the testing location, then turn it slightly to smooth out the level surface; (3) set the trigger mechanism to the desired falling height of 25, 50, or 75 cm; (4) lift the weight until it connects with the trigger mechanism; (5) press the go button on the handheld computer; (6) activate the trigger mechanism while holding the top of the guide rod to keep the instrument steady; and (7) record the load and displacement readings and repeat the same to perform the test and record readings for five times. Analysis of the collected data will provide the repeatable stiffness results.

Loadman PFWD. The Loadman PFWD was originally developed in Finland and used to test granular base courses (see Figure 47). The device utilizes a single 10 kg weight that is dropped from a fixed height of 800 mm (2.6 ft) (Steinert et al. 2005). The Loadman has loading plate sizes of 132, 200, and 300 mm (5.2, 7.9, and 11.8 in.). The device is capable of measuring deflections ranging from 0 to 5 mm (0 to 0.2 in.), with a time of loading between 25 and 30 ms and a maximum dynamic load of roughly 23 kN (5,171 lbf).

The Loadman PFWD (Loadman 2) uses two types of sensors: a load cell and an accelerometer (Steinert et al. 2005). The revised Boussinesq's stress expression is used to determine the modulus from the Loadman results. For each measurement, the Loadman displays the maximum deflection and the calculated bearing capacity modulus, among others. A few other LWD devices are also used in the United States, and these details are documented in the following synthesis sections.

The methods described previously frequently and recently used nondestructive techniques for interpreting stiffness properties of subgrades and unbound bases. The following sections summarize various field practices attempted by several research studies supported by the state DOTs, test-related field experiences, moduli interpretations and comparisons between interpreted moduli and M_R results, and assessments of software used for backcalculations of moduli.

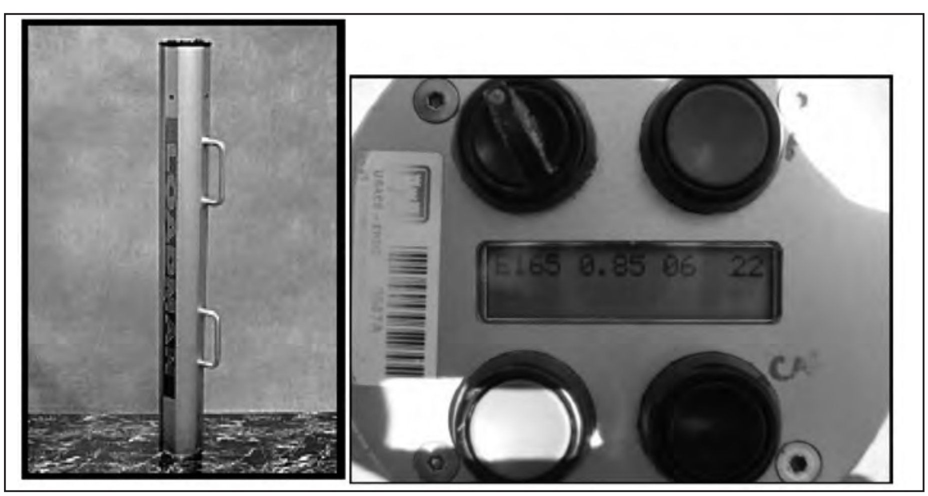


FIGURE 47 Loadman PFWD (*left*) and display portion of unit (*right*) (Steinert et al. 2005).

Because it is difficult to list each of the research papers that have covered the nondestructive and backcalculation studies on pavements, an attempt is made to cover only state DOT–funded research studies that evaluated nondestructive studies since the mid 1990s.

SYNTHESIZED INFORMATION—NONDESTRUCTIVE TESTS

Florida—Subgrades

Choubane and McNamara (2000) performed research for Florida DOT (FDOT) to assess the feasibility of using FWD data to predict the moduli of subsoils. This research described a methodology for using the measured deformation data to predict the modulus and also the compatibility of the FWD data with those measured by Dynaflect. FDOT used Dynaflect data for years, and hence they were supporting research to address the potential use of Dynaflect for field operations. Florida's previous experience with nondestructive deflection testing (NDT) studies has shown that the pavement deflections measured at 36 in. away from the load are appropriate for the determination of the subgrade moduli (Choubane and McNamara 2000).

Based on 300 field FWD studies, the following equation was developed and recommended for pavement design (Choubane and McNamara 2000):

$$E_{\mathrm{FWD}} = 0.03764 \times \left[\frac{P}{d_r}\right] \tag{5}$$

where E_{FWD} is subgrade modulus interpreted from FWD; P is applied load in lbs; and d_r is deflection measured at a radial distance, r, of 36 in. These modulus data from FWD are compared with the moduli determined from Dynaflect data in Figure 48, which suggest a strong correlation between E value predictions by FWD and Dynaflect methods. This approach of using both was recommended by Choubane and McNamara (2000) to FDOT for their moduli assessments of the subgrades.

Ping et al. (2002) studied and compared in situ FWD-determined moduli with laboratory resilient modulus for similar stress conditions close to FWD tests in the field. Results suggest that the backcalculated E_{FWD} is about 1.65 times higher than laboratory resilient modulus. This variation is close to the 1991 AASHTO pavement design guide that recommends a factor of 0.5 to 0.33 be applied to the E_{FWD} to determine the laboratory M_R value, regarded as a design input parameter for flexible pavements.

Idaho—Subgrades

Bayomy and Salem (2004) presented FWD studies conducted on test sections once a year from 1999 to 2002. For each site, the test was conducted at five different stations using two different loads, 8,000 lb and 12,000 lb (Bayomy and Salem 2004). The radial distances between the centerline of the applied load and each of the seven sensors were 0, 8, 12, 18, 24, 36, and 60 in. (0, 20, 30, 45, 60, 90, and 150 cm), respectively. The plate radius on which the load was applied was 5.91 in. These measured values were then analyzed using backcalculation software, Modulus, Version 5.1.

FWD-interpreted moduli were regarded as measured moduli values. Figure 49 compares the FWD backcalculated moduli (referred to in the figure as measured moduli) with predicted moduli (based on regression equations using different soil properties). There is some variation between these measurements, though their trends appear to be the same. Bayomy and Salem (2004) also mentioned the need for more data points for a better assessment of models.

Mississippi—Subgrades and Bases

The field studies supported by the Mississippi DOT are well documented in the literature (George and Uddin 2000; Rahim and George 2003). Research performed by George

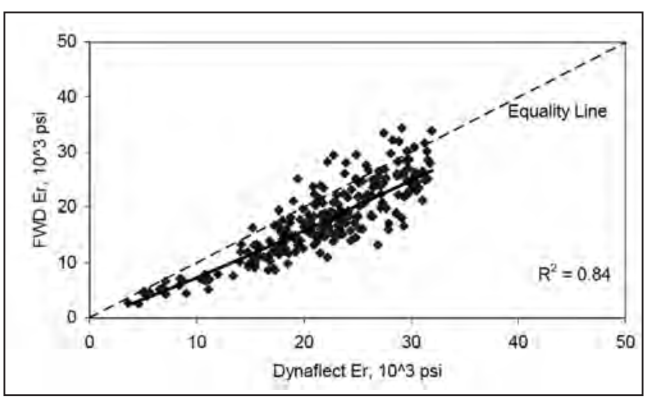


FIGURE 48 Comparisons of E predictions by both NDT methods (Choubane and McNamara 2000).

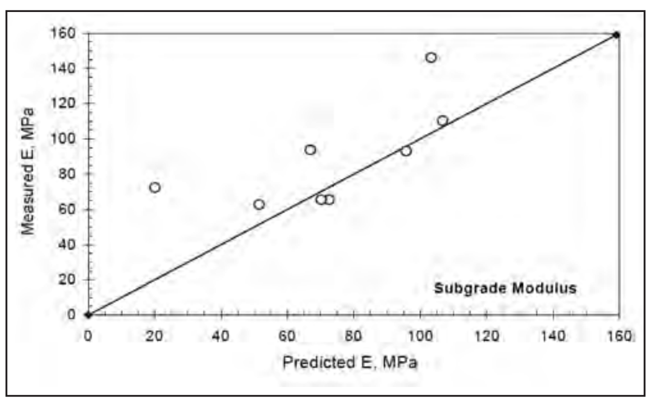


FIGURE 49 Comparisons of moduli predictions by FWD and regression modeling methods (Bayomy and Salem 2004).

and Uddin (2000) aimed at correlating the DCP data to predict field moduli. Subgrade moduli in this study were determined by analyzing the deflection profiles obtained by the FWD.

As part of Mississippi DOT-funded research, FWD studies were conducted on 12 test sections, with two types of subgrades representing both clays and sandy soils (Rahim and George 2003). The main intent of this research was to determine the ratios of resilient modulus values obtained from laboratory and field measurements, for Mississippi subgrade conditions, to verify earlier studies that documented a wide variation between laboratory and field moduli. Von Quintus and Killingsworth (1998) reported that the ratios between moduli from FWD and laboratory ranged from 0.1 to 3.5 based on the LTPP database.

This study used resilient moduli results from the AASHTO TP-46 tests conducted on the cores collected from the same subgrades. Though three backcalculation programs (namely, Modulus 5, FWDSOIL, and UMPED) were initially mentioned, results from only the first two programs were documented in the report. The Modulus 5 backcalculated subgrade modulus values showed a good agreement with the laboratory M_R, and the FWDSOIL backcalculation of subgrade moduli was slightly lower than the laboratory M_R.

Backcalculation analysis of FWD data on subgrades was attempted using a Modulus 5 program developed by Texas Transportation Institute researchers. Each subgrade was subdivided into three layers, and the modulus of each layer was compared in the analysis. FWD measurements were done twice, once on the finished subgrade and the other on the finished pavement surface. $E(\text{Back})_1$ was based on backcalculations using FWD data on the subgrade and $E(\text{Back})_2$ was based on FWD data collected on the pavement surface. Comparisons of both laboratory moduli and field moduli [$E(\text{Back})_2$], backcalculated from both FWD measurements, are presented in Figure 50.

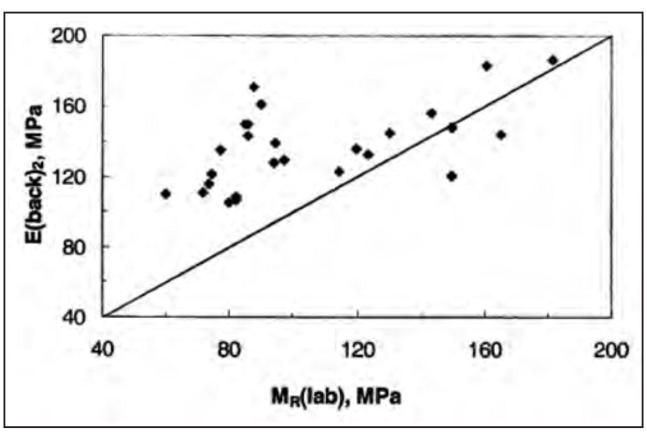


FIGURE 50 Comparisons of moduli predictions by FWD and measurements by laboratory methods (Rahim and George 2003).

The $E(\text{Back})_2$ values are larger than the corresponding laboratory values. Hence, the ratio of values of $E(\text{Back})_2$ and laboratory moduli varied from 0.85 to 2.0, with an average value of 1.4. This study also reported that the moduli measured from FWD tests on the subgrade were smaller and close to laboratory measurements. The FWD data on the pavement sections yielded higher moduli, which was attributed to the higher confinement induced by the pavement sections. These results show that the comparison has less scatter at high moduli (more than 100 MPa), which suggest that FWD predictions of low moduli magnitudes need further scrutiny. The findings from this study were also compared with the LTPP data from Mississippi, and the researchers reported that a good agreement was obtained.

Overall, Rahim and George (2003) acknowledged the need to revise the current factor of 0.33 applied over the FWD moduli, to determine the laboratory moduli, because the findings from this research showed lesser variations between moduli measurements and predictions. The research findings and conclusions presented here are valid for the backcalculation software used in this research.

New England—Subgrades

Malla and Joshi (2006) reported FWD studies and comparison analyses in a research project conducted for New England states. To correlate the laboratory resilient modulus (M_R) values and FWD backcalculated modulus, the LTPP database was accessed. FWD backcalculated modulus data for Rhode Island were not available and hence not included in the comparison analysis. Mean elastic modulus was calculated using backcalculation software MODCOMP, version 4.2. For the purpose of comparison, the average of FWD backcalculated elastic modulus values, corresponding to different levels of drop heights, was compared with the average of laboratory M_R values at confining pressures of 13.8 kPa, 27.6 kPa, and 41.4 kPa. The backcalculated modulus values used are the same for all comparisons.

Researchers noted that the backcalculated modulus values were higher than the laboratory resilient modulus values conducted at the same test site. However, no definite relationship exists between the two values, which were attributed to the difference in years of FWD testing and laboratory specimen sampling and testing. Also, Malla and Joshi (2006) noted that the laboratory M_R depends on soil and stress conditions, whereas E from FWD is related to a single field stress condition. They recommended another approach in which M_R is calculated using bulk and octahedral stresses representative of the subgrade depth, where the stress ratio (ratio of normal stress at the pavement surface to the normal stress at the depth, D) is less than or equal to 0.1 and then compare the calculated M_R with the backcalculated M_R value from FWD studies.

Another study conducted by Steinert et al. (2005) for the New England Transportation Consortium focused on the application of LWD to evaluate the support capacity of pavements during the spring-thaw conditions as well as the adequacy of the base and subgrades during construction.

A PRIMA 100 LWD was used as the primary LWD instrument for this research because it can be used with three different drop weights, three plate diameters, adjustable fall heights, and three deflection sensors. The performance of seven paved and three gravel surfaced roads were monitored during the spring of 2004. All test sites were located in Maine, New Hampshire, and Vermont. One of the gravel surfaced sites located in New Hampshire was monitored during the spring of 2003. Two additional sites in northern Maine were also used for this testing. PRIMA 100 LWD and traditional FWD measurements were taken at a minimum of eight locations at each test site. In addition, Loadman PFWD measurements were taken at spring-thaw test sites in Rumney, New Hampshire.

Clegg Impact Hammer and Humboldt Soil Stiffness Gauge (SSG) measurements were taken at the U.S. Forest Service parking lot during the spring of 2003 and 2004. With the PRIMA 100 LWD, six measurements were taken, each at three different drop heights, at each test location. The first reading was omitted, and the average of the remaining five was used for analysis and comparison. In addition, Loadman PFWD, Clegg Impact Hammer, and SSG measurements were performed at all test locations. Moduli were backcalculated from FWD data using either the DARWIN or EVERCALC programs.

The degree of correlation between moduli backcalculated using FWD and PRIMA 100 LWD was studied (Steinart et al. 2005). Test data from five sites in Maine for which the composite moduli from the FWD were available was used in this analysis. Regression analyses yielded correlation coefficients ranging from 0.34 to 0.95. Higher correlation coefficients were obtained when thin pavement sections were tested.

Loadman PRWD and PRIMA 100 LWD moduli were compared with FWD-derived subbase moduli for two asphalt surfaced test sites in Rumney, New Hampshire (Steinart et al. 2005). The Loadman LWD provided a modulus that is less than the value interpreted by the PRIMA 100 data. Steinart et al. (2005) noted that the PRIMA 100 LWD-interpreted moduli correlates better to FWD-derived subbase moduli ($R^2 = 0.55$) than the moduli obtained from the Loadman LWD ($R^2 = 0.24$). Overall, this research summarized that both LWDs are good tools to determine moduli of base and subbase layers.

For compaction control studies, Steinart et al. (2005) provided equivalent PRIMA 100 base moduli values at various levels of compaction efforts along with corrections based on the moisture content variations. Researchers cautioned that the results are based on the limited set of materials tested in their research and recommended additional testing for verification if these materials are used for other DOTs.

Minnesota—Subgrades and Bases

One of the earlier nondestructive device studies for MnDOT was performed by Siekmeier et al. (1999), in which the Loadman PFWD and Humboldt SSG were used to characterize both subgrade and granular bases for several construction projects in Minnesota. Standard FWD tests using Dynatest were performed at some locations and the moduli were backcalculated by analyzing the FWD data with EVERCALC, a backcalculation software program. The moduli from various devices were compared with those from FWD to determine the ability of LWD and SSG to measure in situ stiffness. Figure 51 presents the moduli of granular bases from various field methods, including LWDs (termed as PFWDs in the figure) and DCP methods.

Also, laboratory resilient modulus tests were performed on field cores, and their results were compared with field-derived moduli for developing correlations between field and laboratory moduli. The FWD backcalculated moduli varied between 190 and 230 MPa, which were different from those determined by other methods. Siekmeier et al. (1999) attribute this variation to the confinement provided by the pavement backcalculation program's simplifying assumption by not accounting for pavement edge effects and variations of pressures exerted by the devices on the overlying surface

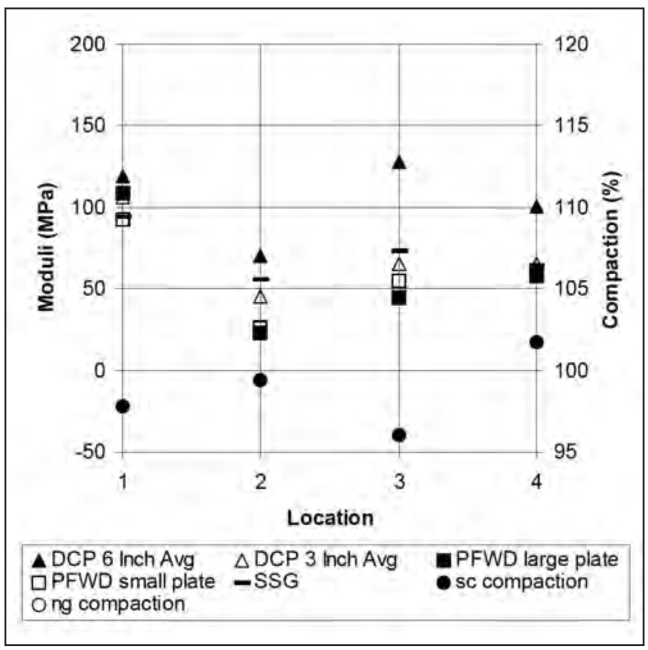


FIGURE 51 Comparisons of moduli of bases from various field studies (sc = sand cone test and ng = nuclear gage) (Siekmeier et al. 1999).

during the testing. The resilient moduli measured from the laboratory tests were found to range between 180 to 320 MPa for bulk stresses of 0.1 to 0.3 MPa (Siekmeier et al. 1999). Siekmeier et al. (1999) and Siekmeier (2002) cited that the FWD backcalculated moduli are comparable with the resilient moduli from laboratory measurements at lower bulk stresses than at higher bulk stresses.

Figure 52 presents the moduli of subgrades as determined by the in situ devices used in this research. Similar trends, as seen in the previous figure, can be seen here. Compaction trends did not match well with the subgrade soils.

Subsequent to this research work, the nondestructive investigations supported by MnDOT focused on portable and light weight FWDs for moduli measurements (Hoffman 2004). Most of these studies focused on quality assessments related to compacted bases and subgrades. Hoffmann et al. (2004) presented an LWD-type device known commercially as PRIMA 1000 for quality assessments of compacted granular bases using the stiffness measurements. A spectral-based data interpretation method, based on the concept and measurement of the frequency response function and a single-degree-of-freedom mechanical model, was employed to interpret the true static stiffness of compacted base layers from PRIMA 100 measurements. Results showed a good agreement with known and calibrated stiffness properties of the materials.

Another study conducted by Petersen and Peterson (2006) presented field data in Minnesota using both PRIMA 100 (LWD) and GeoGauge devices in determining the moduli of the compacted layers. A total of 40 and 25 tests were performed for GeoGauge and PRIMA 100 devices, respectively, at a site located along a portion of a MnDOT TH 53 Trinity Road project. The main intent of this road project was to demonstrate the intelligent compaction technology using a vibratory compaction roller, Caterpillar.

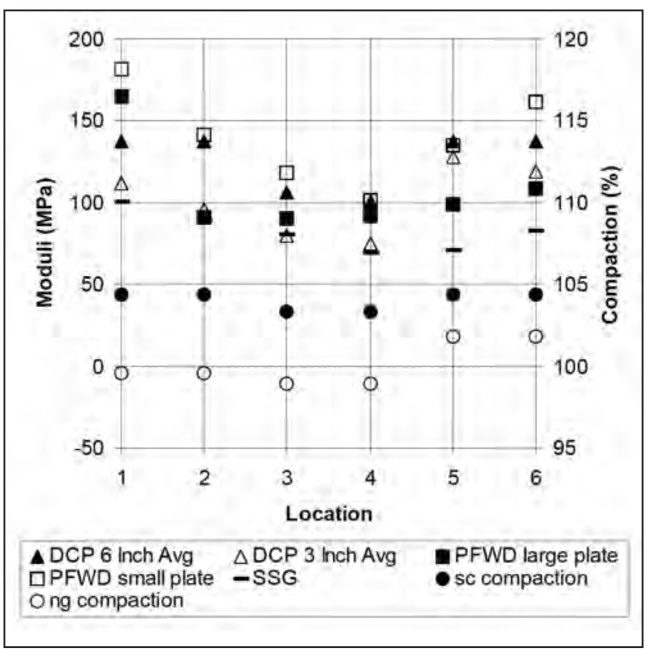


FIGURE 52 Comparisons of moduli of subgrades from various field studies (sc = sandcone and ng = nuclear gage) (Siekmeier et al. 1999).

Both GeoGauge and LWD data correlated well and also showed good agreement with the compaction meter values provided by the Caterpillar compaction software. Figure 53 presents the LWD data, which showed that it follows normal distribution trends at all the different heights of the fall of the hammer. These results are also in good agreement with those measured by GeoGauge. This whole research effort was to evaluate the QA studies on the compacted subgrade, and not on the moduli assessments. Nevertheless, the stiffness measurements of compacted subgrades and unbound bases could be used for the field determination of moduli properties needed for pavement design.

Swenson et al. (2006) studied moisture effects on the measurements of several laboratory and field devices and their interpreted moduli values. Four types of subgrade soils were studied in various sizes and shapes. In the field studies, this study reported a significant scatter of moduli from various field measurement devices, including DCP, PRIMA 100, GeoGauge, and others. Overall, the results showed that both moisture and density have a measurable effect on the moduli of all four tested soils.

White et al. (2007) recently completed another research study for MnDOT that focused on compaction quality assessments of the subgrades based on the moduli measurements made using LWDs. Two types of LWDs were utilized in this research: the ZFG 2000 LWD and KEROS LWD.

The ZFG 2000 LWD device was manufactured by Zorn Stendal, Germany (www.zornonline.de), and complies with German specifications for road construction. Deflections are measured using accelerometers for various load pulses, and the data are then analyzed to determine the dynamic deflection modulus. The KEROS LWD device was manufactured by Dynatest, Denmark (www.dynatest.com). The device is equipped with a load cell to measure the impact force from the falling weight and a geophone to measure the induced deflections at the ground surface. Dynamic modulus was then determined using a modified Boussinesq's equation. More details of both LWD procedures are presented in White et al. (2007).

White et al. (2007) attempted to correlate LWD predicted moduli with the resilient moduli determined from laboratory testing on the Shelby tubes from the field site known as the MnROAD project site. The subgrade soils contain a mixed glacial till and a sandy soil with silt and gravel.

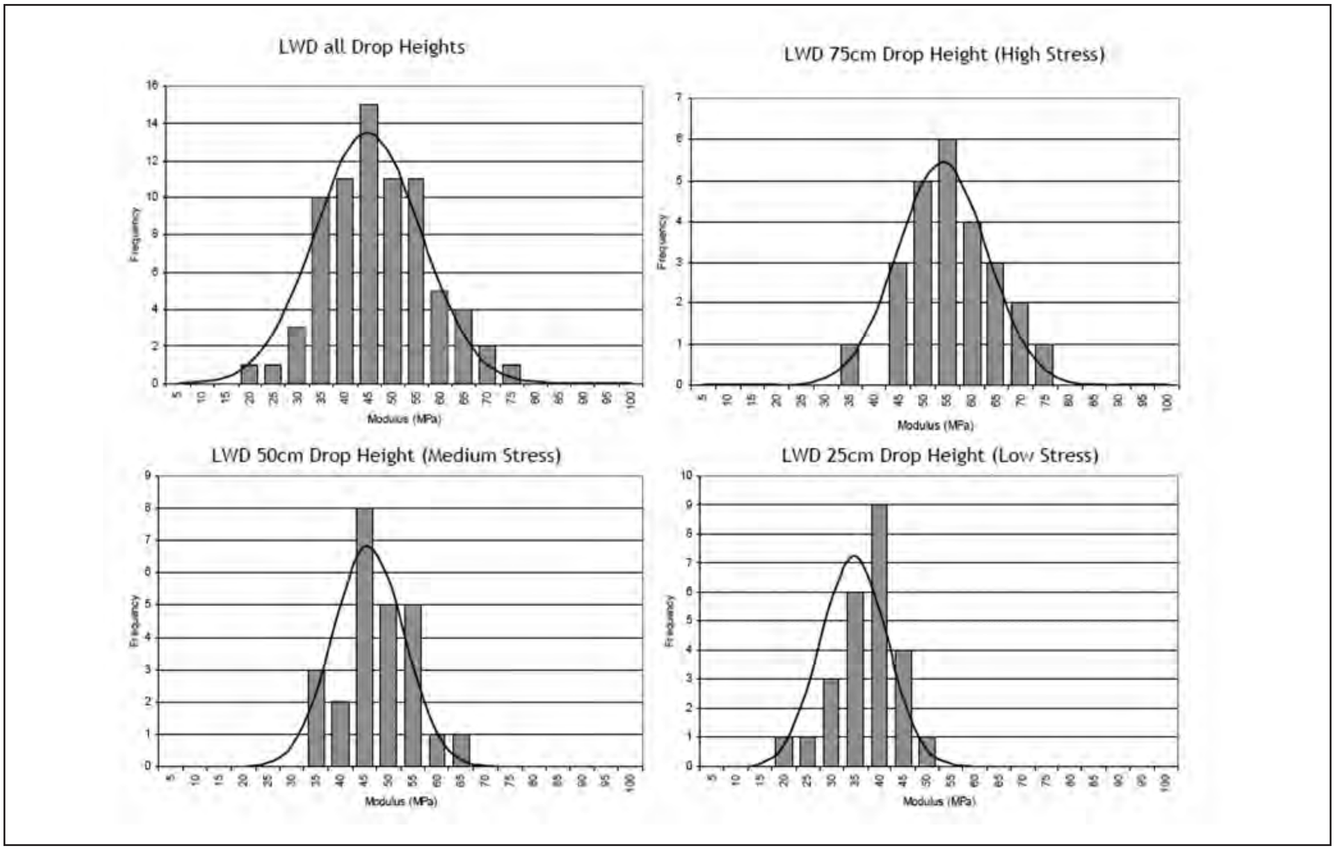


FIGURE 53 LWD moduli predictions and their distribution (Petersen and Peterson 2006).

AASHTO's T-307 procedure was followed for laboratory resilient modulus testing. The LWD studies were also conducted on the compacted subgrade using both devices, ZFG 2000 and KEROS. Figure 54 shows these devices on the compacted subgrade.

FIGURE 54 LWD devices in field operation (White et al. 2007).

E_{LWD} is a function of maximum deformation (or strain) under an applied plate contact stress, and these strains are total strains and not resilient strains. Because of the differences in strains, both moduli (M_R from Laboratory and E_{LWD}) are not considered the same, and hence White et al. (2007) used the secant modulus (M_s) from the permanent strain and resilient strain data obtained from the resilient modulus test. The secant moduli were then compared with E_{LWD} data. Figure 55 presents the three different moduli, E_{LWD}, M_R, and M_s determined from these studies. Because of high contact stresses imposed by the LWD tests, the M_R data at high confining and deviatoric stresses (42 kPa and 68.9 kPa, respectively) were used in another set of comparisons, which are presented in Figure 56.

Some of the major findings from this research as seen from these two figures are that both LWDs provided different dynamic moduli for the same subgrade owing to the differences in the methods adopted by these devices to measure the deformations in the field. One uses a geophone and the other uses an accelerometer. The "KEROS" E_{LWD} (moduli)

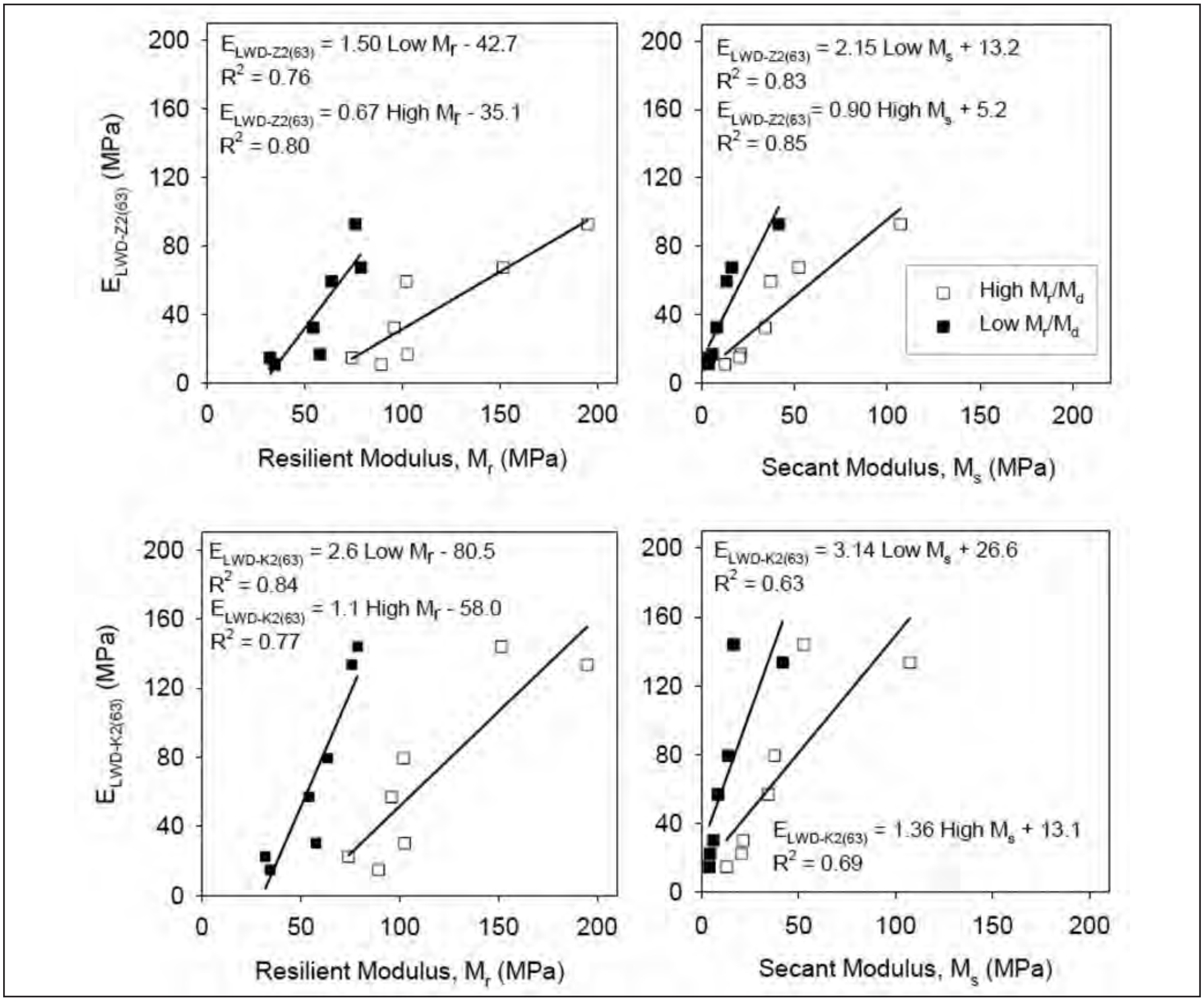


FIGURE 55 Comparisons of moduli determined from LWD and maximum and minimum resilient modulus from repeated load triaxial tests (White et al. 2007).

is on average 1.75 to 2.2 times greater than "Zorn: E_{LWD} (moduli). This study showed the effects of plates used in the equipment on the moduli values determined. A good correlation was obtained when moduli of LWD are correlated with the resilient moduli at select confining and deviatoric stresses (see Figure 56). A similar relationship was recorded when the LWD moduli were correlated with that of secant moduli values.

For compaction assessments, White et al. (2007) developed several tables that list LWD moduli values along with other in situ penetration test numbers for quality assessments of compaction of the subgrades. Both granular and cohesive subgrade soil types are listed in these tables. These tables describe the soils tested in the original investigation.

Louisiana—Subgrades and Bases

Abu-Farsakh et al. (2004) performed two types of nondestructive field tests to assess the stiffness properties of the compacted subgrades and bases, including stabilized layers. The main intent of these investigations was to address the applicability of these tests to provide realistic stiffness properties that are needed in both mechanistic pavement designs and for quality assessments of compaction. Two devices were evaluated, which included GeoGauge and an LWD. A PRIMA 100 was used for the LWD studies. To assess the moduli predictions, several FWD tests, using a trailer-mounted Dynatest, were conducted and the deflection data were analyzed using the ELMOD 4.0 backcalculation software program. All tests were conducted on both laboratory-prepared compacted soils and field subgrades.

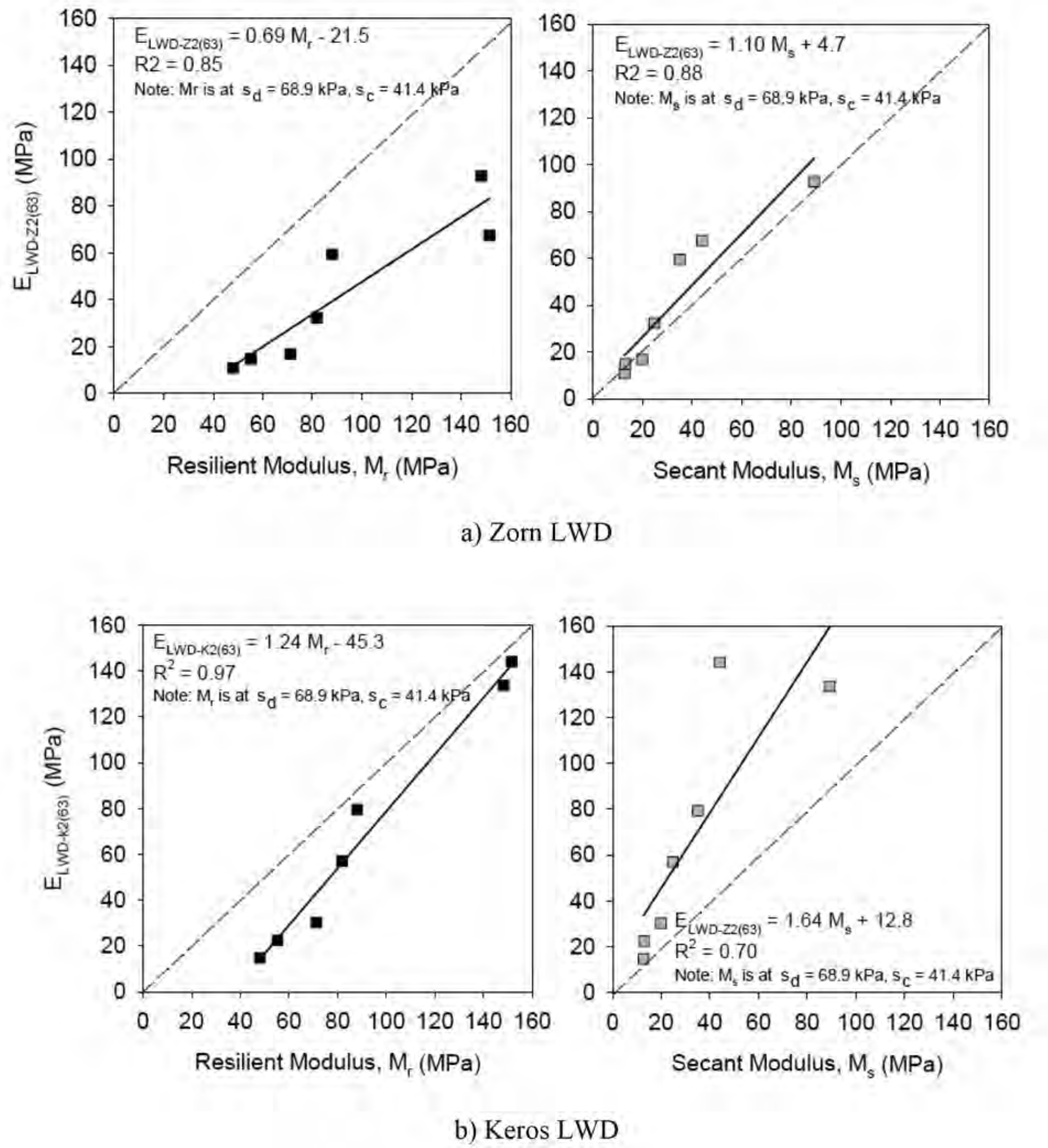


FIGURE 56 Comparisons of moduli determined from LWD and resilient modulus triaxial tests at deviatoric stress of 68.9 kPa (White et al. 2007).

In the LWD studies, tests were conducted on the same material compacted with three different compactive efforts. In each case, the coefficient of variation (C_v), an indicator for repeatability, was determined and these results showed that they vary from 2% to 28%. These results are plotted against the stiffness property, E_{LFWD}, determined from the PRIMA 100 tests as shown in Figure 57. The C_v value reduces with an increase in stiffness, indicating that this LWD device provides repeatable results at a higher stiffness of subgrades and bases.

Figures 58 and 59 present comparisons of LWD moduli with FWD moduli (M_{FWD}) and CBR properties, along with the regression expressions. The FWD modulus was regarded as the resilient modulus in their research. The correlation developed for CBR was poor as a result of a large scatter in

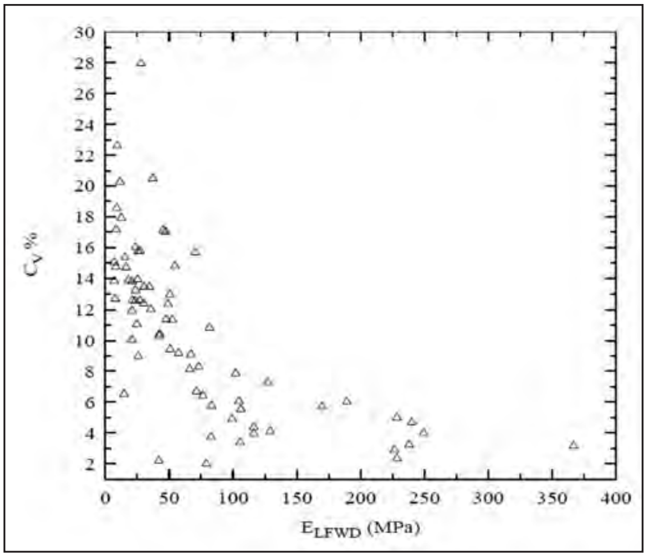


FIGURE 57 LWD moduli versus coefficient of variation, C_v (Abu-Farsakh et al. 2004).

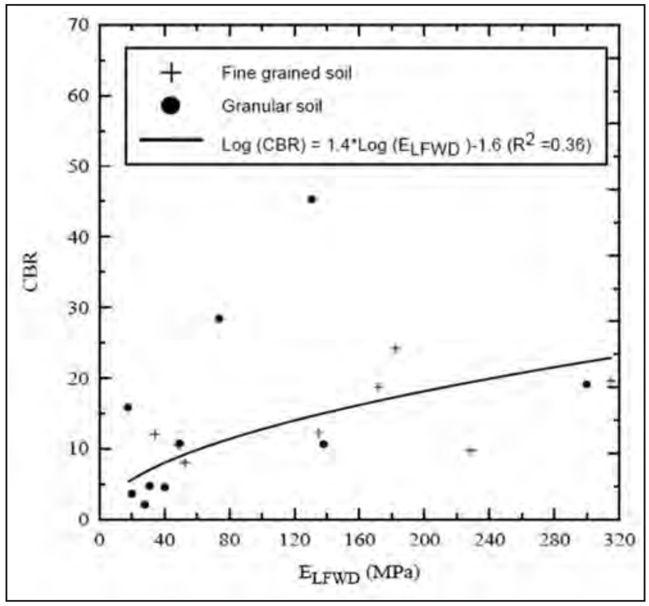


FIGURE 58 Correlations between LFWD modulus and CBR properties of different soil types (Abu-Farsakh et al. 2004).

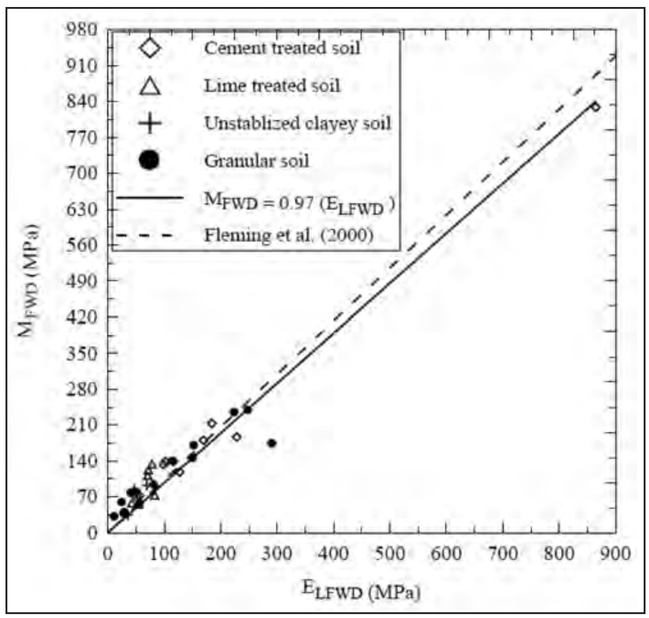


FIGURE 59 Correlations between LFWD modulus and FWD modulus properties of different soil type (Abu-Farsakh et al. 2004).

the test results. The correlation developed between moduli of FWD and LWD was strong, suggesting that the LWD provides similar moduli values as the FWD.

For GeoGauge results, the C_v values varied between 0.4% and 11.4%, indicating excellent repeatability with this device (Abu-Farsakh et al. 2004). This study also reported that there is a strong correlation between E_G values from GeoGauge with the field resilient moduli, M_{FWD} from FWD. A good correlation was obtained between E_G value from GeoGauge and the CBR value of compacted subgrade and base materials. Figures 60 and 61 present these trends, along with regression expressions to determine both FWD moduli and CBR values from GeoGauge moduli.

No laboratory tests were reported in this research for the determination of resilient moduli properties of the same compacted materials. Hence, a comprehensive comparison analysis between nondestructive techniques and laboratory-determined moduli could not be performed. Nevertheless, the comparisons between the nondestructive methods offer considerable insights into the applicability of LWD and GeoGauge in providing the stiffness properties of the subgrades and bases.

The Abu-Farsakh et al. (2004) study reported that correlations were obtained from the field test-based methods for interpreting moduli properties. The authors presented several advantages of GeoGauge, including convenience in operating the device, quick test, and durability of the device. This study showed a good match of moduli data from GeoGauge with FWD for both subgrades and bases tested in this research. Similar results were observed for LWD; however, this device was reported as not handy. Researchers requested further tests on both LWD and GeoGauge to address the effects of time of testing (different time periods in a day) on the moduli results of stabilized bases before implementing these in the field.

New Mexico—Subgrades

Lenke et al. (2003) performed field investigations to address compaction quality of aggregate bases using a GeoGauge. It was observed that GeoGauge is capable of determining stiffness properties in the field, and these stiffness properties of compacted layers show a strong

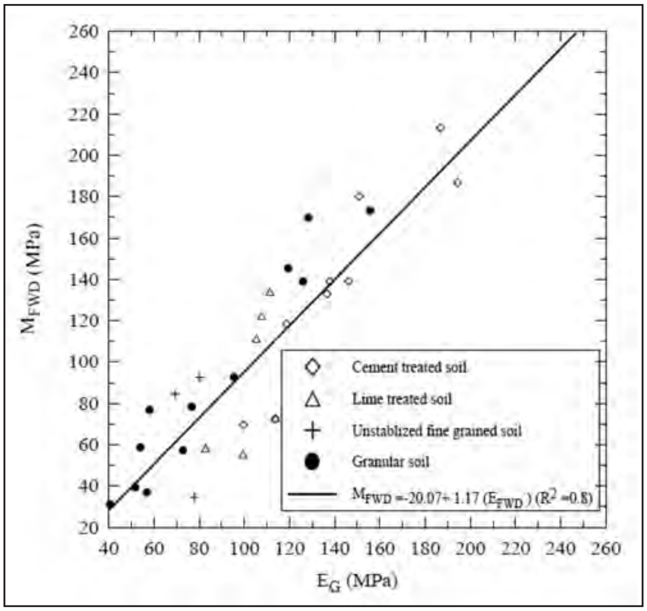


FIGURE 60 Correlations between GeoGauge modulus and FWD backcalculated modulus properties (Abu-Farsakh et al. 2004).

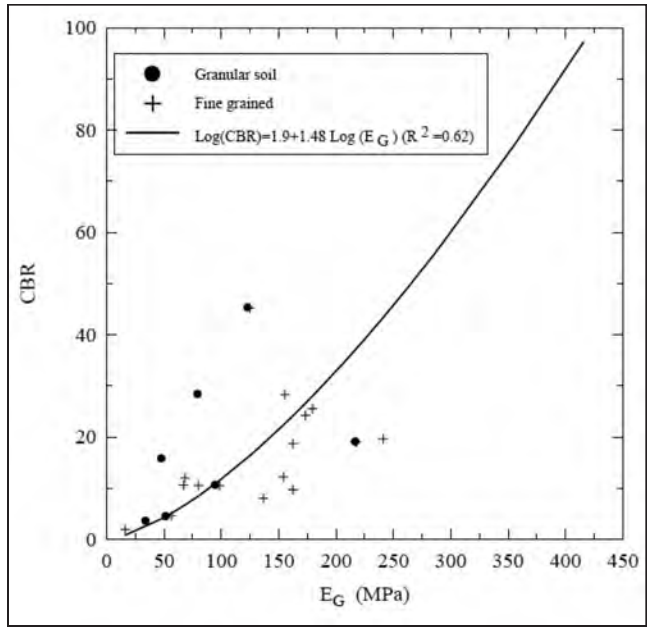


FIGURE 61 Correlations between GeoGauge modulus and CBR property (Abu-Farsakh et al. 2004).

dependency on the number of passes of rollers used in the field. Figure 62 presents the field moduli predicted by GeoGauge versus the number of passes applied on the base material in the field.

The device was also used in the laboratory on different compacted subgrade soils prepared in the laboratory molds, and these results were reported to be influenced by the boundary conditions induced by the rigid molds (Lenke et

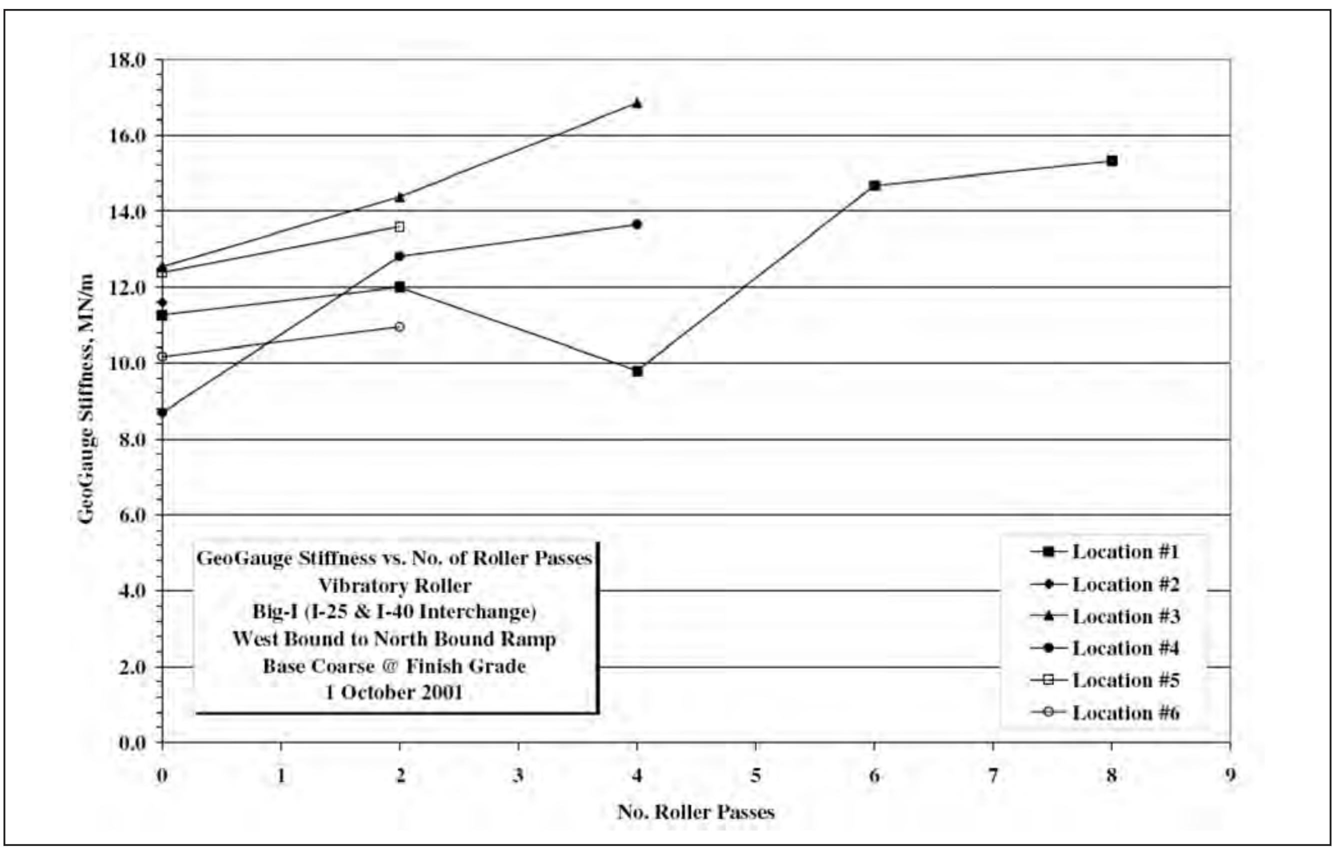


FIGURE 62 Effects of number of passes on GeoGauge moduli (Lenke et al. 2003).

al. 2003). It was observed that this device was valuable for assessing field compaction control utilizing the moduli data. However, the establishment of such moduli data from laboratory tests was still not successful because of the boundary effects of the compaction molds used in the laboratory.

Wisconsin—Subgrades and Bases

Edil and Benson (2005) performed research investigations to address the stiffness and stability aspects of subgrades using both the GeoGauge and DCP. Results from these test methods used in 13 project sites across the state of Wisconsin were analyzed and correlated with various soil properties. Figure 63 presents GeoGauge SSG results on both coarse- and fine-grained soils from the project site locations. These SSG values ranged from 0 to 12.1 MN/m, and this range is dependent on the material type and the compaction state. The mean SSG values for coarse- and fine-grained soils are 6.3 and 5.6 MN/m, respectively.

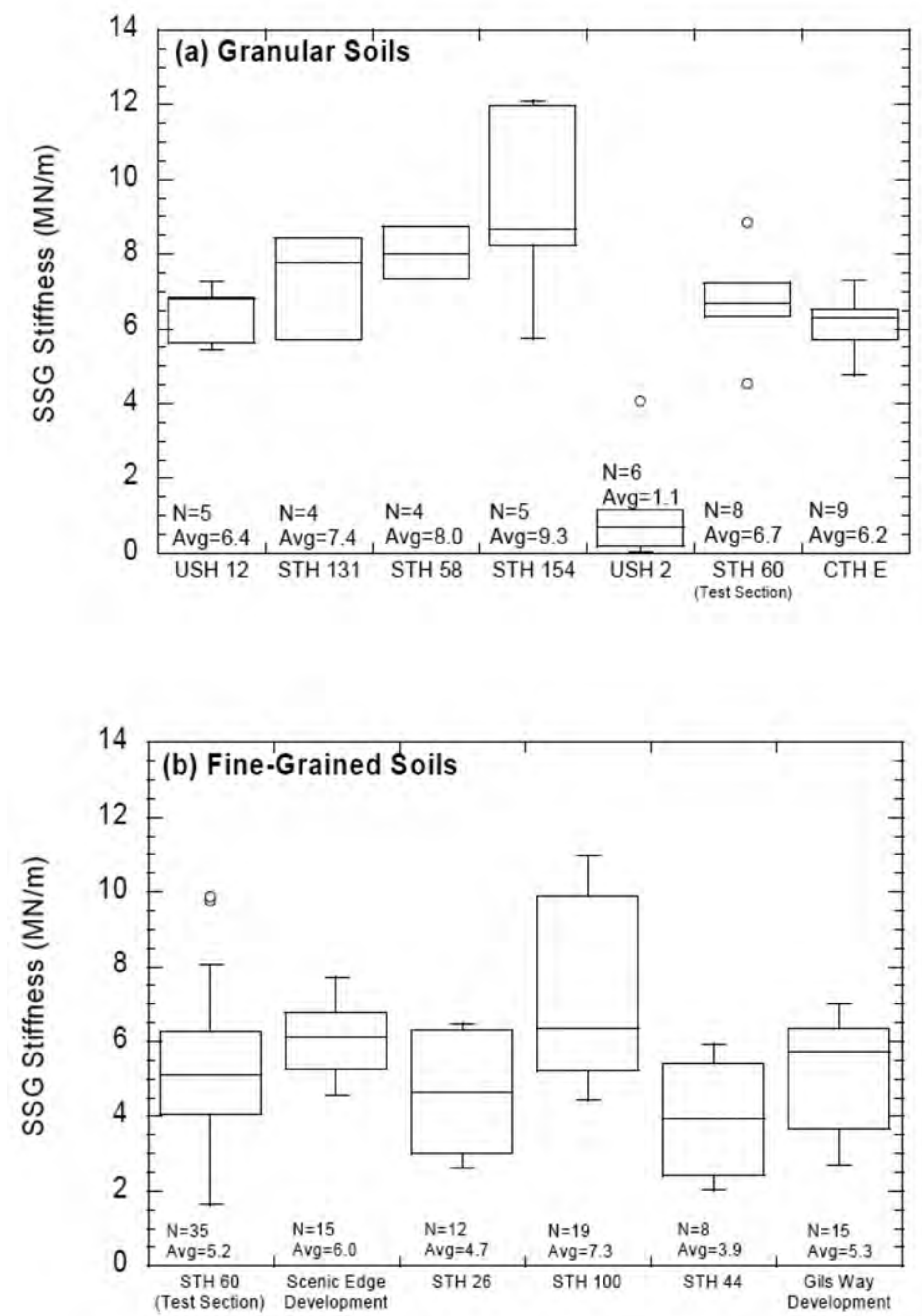


FIGURE 63 GeoGauge stiffness (SSG) measurements in Wisconsin test sections (Edil and Benson 2005).

As part of this research, a separate study performed by Sawangsuriya et al. (2002) documented several laboratory tests and their moduli values. Figure 64 presents some of these results including SSG, resilient modulus–based RLT tests, conventional triaxial tests, seismic bender element–based tests, and RC tests. These tests are known to provide moduli from different types of tests such as static, dynamic, and seismic or nondestructive tests at different shear strain amplitudes, and a comparison of results shows a complete moduli degradation curve with respect to the shear strain amplitudes.

The GeoGauge stiffness measurements are representative of 10^{-3}% to 10^{-2}% strains, whereas the stiffness measurements of bender element and RC tests are close to small-strain conditions (10^{-3}%). Resilient modulus triaxial test results are representative of medium shear strain levels, similar to the GeoGauge range. The moduli from conventional static-type triaxial tests are close to secant moduli values at large shear strains of 10^{0}% to 10^{-1}%. Other analyses of these results showed that the SSG value depends on compaction moisture content and dry unit weight; however, their trends are obscured by the large dispersion in the test data of the several types of materials tested in this research (Edil and Benson 2005). This study also indicates that the GeoGauge showed good potential for future application in the pavement and subgrade property evaluation during the construction phase (Edil and Benson 2005).

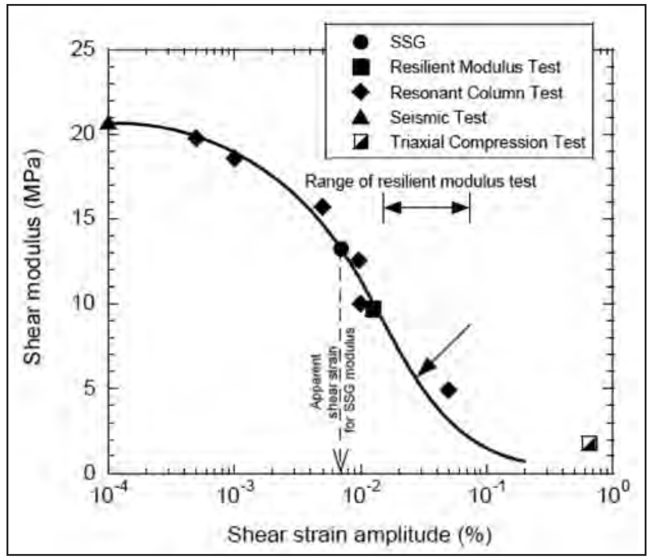


FIGURE 64 Shear modulus of a granular soil from different types of laboratory tests (Sawangsuriya et al. 2002).

Texas—Subgrades and Bases

Several nondestructive test studies were performed for the TxDOT since the early 1990s. The following summarizes a few of these studies and their findings related to resilient properties of subgrades and bases. Nazarian et al. (2003, 2005) and Nazarian et al. (2006) performed both laboratory and field studies in different parts of Texas, and the aim of these studies was to correlate both laboratory and field moduli and develop a methodology to determine moduli for pavement design. For the backcalculation analysis, the MODULUS program was used for analyzing the FWD test data.

An SPA was also introduced to measure the moduli of pavement layers. The SPA lowers transducers and sources and digitally records deformations induced by a pneumatic hammer. A complete testing cycle takes 1 minute, and the moduli results can be determined in the field itself.

For resilient moduli determination, M_R values are either interpreted using three-parameter expressions whose constants are established in earlier experimental studies or by conducting tests on soil samples from the field at high confining and deviatoric stresses. Stresses for the three-parameter expression were estimated using the KENLAYER program simulating field conditions. FWD and SPA moduli were different from one another, with the SPA moduli being 70% higher than the corresponding FWD moduli. Comparing the laboratory resilient moduli and the nondestructive moduli of bases and subgrades, the variation was considerable and significant (Nazarian et al. 1995). The laboratory moduli are less than the field moduli from nondestructive tests by 10% to more than 100%, and this variation was attributed to specimen differences, sample disturbance, and time effects.

In a different research study, SPA, FWD, and Dynaflect devices were used to measure moduli of seven test sites in Texas (Nazarian et al. 2003 and Meshkani et al. 2004). Table 10 presents the SPA results of both bases and subgrades. The average moduli results of subgrades varied from 207 to 570 MPa, indicating that the subsoils tested were soft to stiff cohesive materials. The large coefficients of variation indicate a wide variation in the material type from point to point at each site.

Meshkani et al. (2004) reported another TxDOT-funded research project in which researchers developed an algorithm to predict design moduli based on the seismic modulus and nonlinear parameters of each layer. Seismic modulus is similar to other backcalculated moduli from nondestructive seismic tests. Nonlinear parameters were developed from FWD results. SPA was also used in this research for the same purpose. This research showed the use of FWDs to predict nonlinear resilient modulus expression–related constants, which in turn can be used to determine the design moduli values. Also, SPA was used to address the compaction QC of pavement layers. Overall, the research performed with TxDOT led to the development and application of new devices such as SPA and PSPA as well as new methodologies to estimate design moduli using nonlinear material–related parameters.

TABLE 10
STIFFNESS RESULTS (Nazarian et al. 2004)

Site No.	Road	Average Modulus from SASW Tests, MPa*		Effective Stiffness from IR Test
		Base	Subgrade	
1	FM 977A	4075 (41%)	353 (53%)	672 (45%)
2	FM 977B	1551 (52%)	569 (50%)	1044 (25%)
3	FM 977C	3122 (36%)	207 (53%)	597 (42%)
4	FM1124	2900 (44%)	295 (39%)	834 (41%)
5	FM1935	3129 (47%)	241 (60%)	662 (40%)
6	FM2446	2535 (55%)	276 (30%)	523 (45%)
7	FM2780	2932 (65%)	325 (45%)	481 (60%)

** Number in parentheses corresponds to the coefficient of variation*

An implementation project conducted for TxDOT discussed the development of DSPA to determine the moduli of bases and subgrades. A step-by-step measurement procedure was also developed (Nazarian et al. 2006). This procedure allows a rapid measurement and interpretation of moduli. This device was also used for field compaction QC. Typical test data showing the field target moduli are presented in Figure 65.

The techniques can be used to address the stiffness variations with moisture fluctuations and develop design moduli assessments that account for the variations of moduli with moisture changes. Overall, DPSA is still new to the nondestructive field in pavement geotechnics and more studies are needed to address the full potential of this handy device, which can provide stiffness parameters in a quick turnaround time.

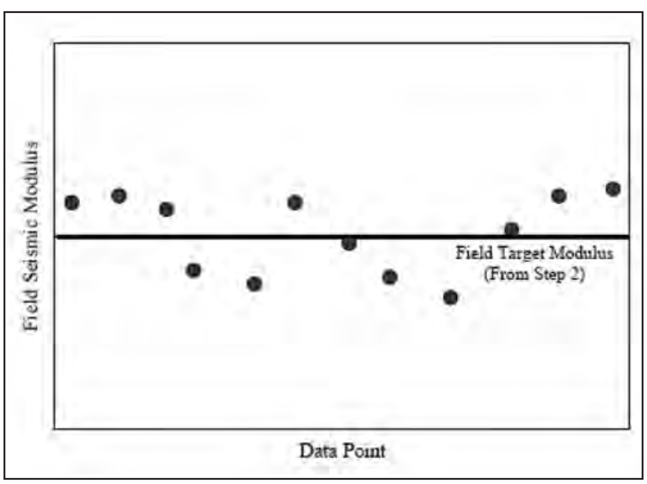


FIGURE 65 Field seismic modulus for compaction QC (Nazarian et al. 2006).

FINAL SUMMARY ON NONDESTRUCTIVE METHODS

The following list summarizes the salient findings from the DOT-funded studies related to resilient moduli property interpretations using nondestructive test methods:

- Among nondestructive field methods, most DOT agencies use FWD tests for moduli determination of pavement layers. Both KUAB and Dynatest devices are primarily utilized. Also, these agencies use different backcalculation programs to analyze the FWD results. Because the predictions of moduli using the FWD do not match the laboratory resilient moduli of base and subgrade layers, the 1993 *AASHTO Guide for Pavement Design* recommended that a fraction of FWD moduli be used as the design resilient modulus value for the mechanistic pavement design. Research studies supported by Mississippi, Minnesota, Texas, and other DOTs confirmed these variations, and the range of variation appears to depend on several factors, including soil type, backcalculation programs used, and others.
- The moduli definitions used by various tests in the mechanistic pavement design explain the variations with respect to strain levels. At small shear strains, the shear moduli and related elastic moduli are high and constant. These moduli will then decrease with an increase in shear strain levels. The strains imposed on bases and subgrades using nondestructive field test methods are close to small strains and hence moduli values are large when compared with laboratory RLT tests, where the strains are of medium range. Nazarian et al. (1996) and Edil and Benson (2005) provided more insights into the variations in moduli at various shear strain levels.

- It is important to mention that the state DOTs do not use the same backcalculation program for interpreting the resilient moduli properties. Currently, several software programs are available with different algorithms to backcalculate moduli. According to the Pavement Design group survey , the most used programs are EVERCALC and MODULUS.
- GeoGauge, another nondestructive device used for stiffness measurements, provides stiffness values of the subsoils based on the analysis of deformations measured by applying a harmonic load. Stiffness properties measured are related to a shallow depth of soil layer and are valid for medium levels of shear strains. A few studies showed a good match between GeoGauge moduli and FWD moduli. Correlations between GeoGauge moduli and resilient moduli still need to be developed.
- Another device known as the PSPA was recently introduced, and its potential use in providing reliable moduli properties of base and subgrades was recently investigated. An extension of this device, the DSPA, was also recently evaluated. Though this device holds considerable initial promise, it still requires more research to fully evaluate the potential of this device for determining the moduli of subsoils.
- Several LWDs were addressed in many DOT-funded research studies. These devices including PRIMA 100, LOADMAN PFWD, ZFG 2000, and Dynatest/KEROS were evaluated in several studies funded by Minnesota, Wisconsin, and Louisiana DOTs. Moduli interpreted by most of these devices showed good correlations with FWD moduli, though not always matching with the FWD moduli. Nevertheless, the moduli trends with respect to soil type and soil compaction are similar, and hence it is possible that these devices could be used to predict resilient moduli of compacted subgrades and unbound bases. ASTM has recently approved a standard test procedure for performing LWD tests in the field. The intent is to standardize a test procedure using LWDs with load cells to measure the deflection and modulus of compacted subgrades in the field. Another standard for LWDs without load cells is currently under development (J. Siekmeier, personal communication, Aug. 21, 2007; K.C. Kessler, personal communication, Aug. 21, 2007).
- Irwin (1995) summarized various problems noted by a discussion group and then outlined methods to overcome a few of these problems. Interpretations of moduli from nondestructive devices yield moduli of subgrades at considerable depths, and hence it is important to address the effects of confining and deviatoric stresses on the moduli values, which in turn should be properly accounted for in the triaxial tests. Otherwise, comparisons will not be meaningful. Also, the stresses imposed by the loading mechanisms of certain LWDs are quite small when compared with FWDs, and this may result in different moduli, because strains experienced in the subgrades are different for different stress conditions.
- The majority of the new nondestructive devices show a considerable potential to be used for quality assessments of compacted subgrades and unbound bases. A recent research study also correlated the moduli from LWDs with the parameters measured in the intelligent compaction devices. Though certain issues such as moisture and temperature effects on the moduli properties of field sections still need to be addressed, the overall potential of these devices as alternatives to nuclear gauge devices for compaction quality assessments are commendable. Further research is expected in these areas.

INTRUSIVE METHODS

Intrusive or in situ penetration methods have been used for years to determine moduli properties of various pavement layers. Intrusive methods can be used for new pavement construction projects and also in pavement rehabilitation projects wherein the structural support of the pavement systems can be measured (Newcomb and Birgisson 1999). Various intrusive methods are briefly reviewed here and then a summary is provided of the findings from various state-funded research projects.

Dynamic Cone Penetrometer

The DCP is a widely used in situ method for determining the compaction density, strength, or stiffness of in situ soils. The DCP is a simple testing device, wherein a slender shaft is driven into the compacted subgrades and bases using a sliding hammer weight and the rate of penetration are measured. Penetration is carried out as the hammer drops to reach the desired depth. The rod is then extracted using a specially adapted jack. Data from the DCP test are then processed to produce a penetration index, which is simply the distance the cone penetrates at each drop of the sliding hammer. In brief, the DCP is a miniature version of the Standard Penetration Test method with a conical tip.

Figure 66 presents a schematic of DCP used for field investigations. The hammer weight and height of drop configurations of DCPs vary from one state to another. Hence, these details should be included when discussing the results of the QA studies utilizing this equipment. An ASTM standard on the DCP method was introduced in 2003 (ASTM D6951-03). Typically, in this test, the measured soil parameter from the test is the number of blows for a given depth of penetration. Several parameters from DCP tests are typically determined and these are termed as dynamic cone resistance (q_d) or DCP index (DCPI) in millimeters per blow or inches per blow or blows per 300 mm penetration. These parameters are used

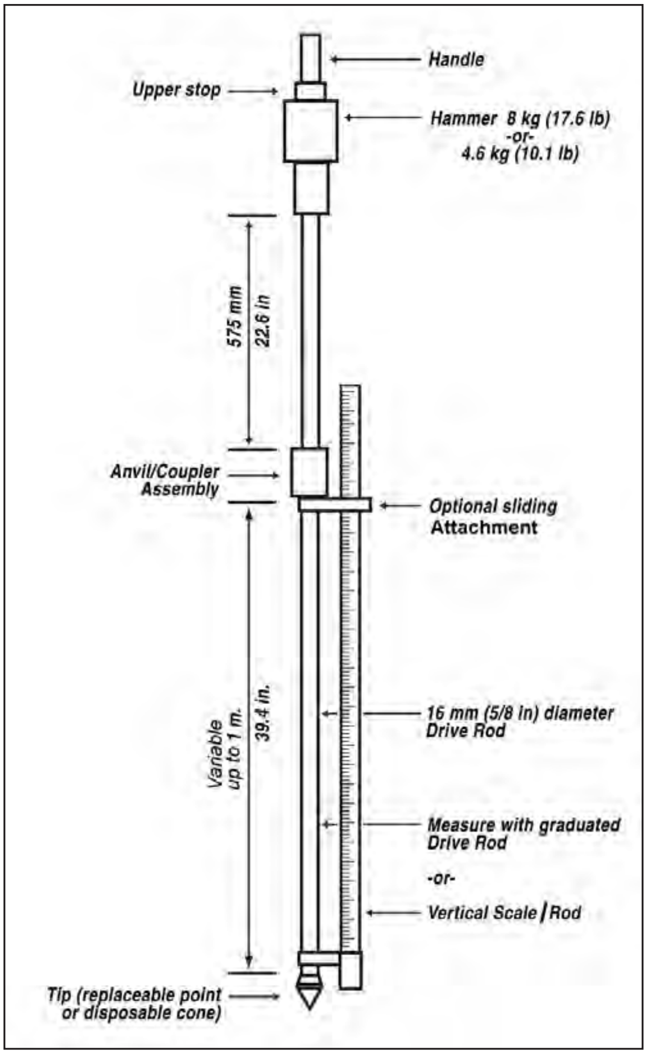


FIGURE 66 Schematic of dynamic cone penetrometer (ASTM D6951-03).

to evaluate the compaction density, strength, or stiffness of in situ soils.

One major limitation reported in the research studies is the lack of standardization of the testing devices. Different size cones, hammer weights, and heights of drop have been used in these studies, which result in different energies applied by each device. As a result, the parameters measured from a particular study and the correlations developed from that study could not be applied elsewhere if a different type of DCP was used. Practitioners and researchers should always record the potential energy applied with the DCP device when used in the field conditions.

Stiffness Predictions by Dynamic Cone Penetrometer

Several researchers have developed design charts showing correlations between resilient modulus (M_R) or stiffness of subgrades and bases and the penetration parameters measured from the DCP test. Amini (2003) and Salgado and Yoon (2003) provided a summary of these available relationships in the literature. Chai and Roslie (1998) developed the following relationship between DCP parameters and soil subgrade modulus backcalculated from the FWD studies:

$$E \text{ in MPa} = 2224 \times \text{DCP}^{-0.99} \quad (6)$$

where DCP is measured in blows per 300 mm penetration. Overall this correlation indicates that the FWD moduli are inversely proportional to the DCP parameter measured in the field.

Hassan (1996) developed a correlation of M_R with the DCPI parameter (Equation 7). This correlation is valid for the materials tested in the original investigations. The compaction moisture contents varied between optimum and wet of optimum:

$$M_R \text{ in psi} = 7013.0 - 2040.8 \ln(\text{DCPI}) \quad (7)$$

where the DCPI is in inches per blow.

George and Uddin (2000) correlated M_R of subgrades as a function of DCPI, moisture content, liquid limit, and density of subgrades. In this research, both manual and automated DCPs were used. Figure 67 presents a typical comparison of both DCP results, which indicate no differences between both operations on the DCP measurements.

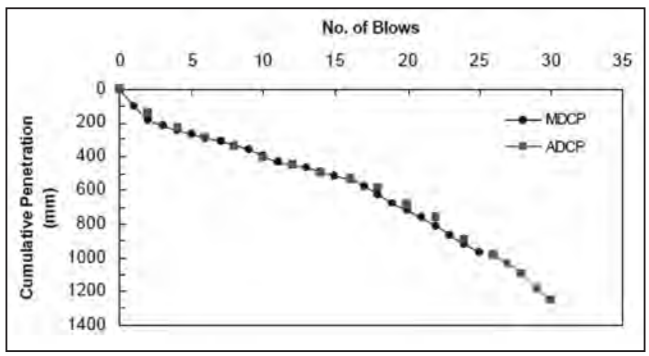


FIGURE 67 Comparisons between ADCP and MDCP results (George and Uddin 2000).

The DCPI was then determined for each layer by taking the slope of the plots. The change in slope defines the variations in layers in the test. Once DCPI values of subgrades were determined, they were used in the correlation analysis with the resilient moduli data from the laboratory tests conducted on the cores collected from different depths.

From the laboratory results, data for a confining pressure of 14 kPa and a deviatoric stress of 37 kPa were used as moduli parameters for the analysis. Figure 68 presents a correlation between resilient moduli and DCPI in millimeters per blow of the corresponding subgrade layer for fine-grained soils.

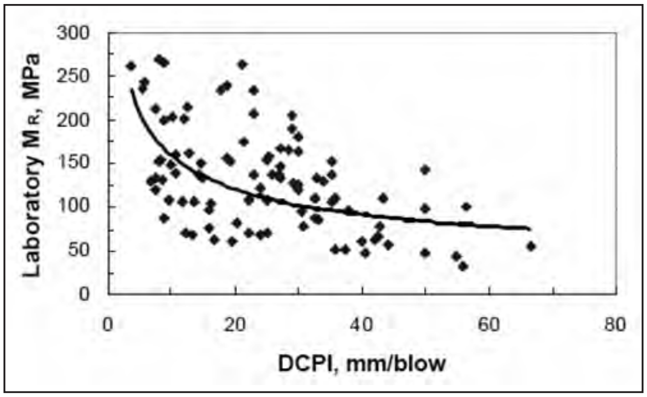


FIGURE 68 Correlation between resilient modulus and DCPI for fine-grained soils (George and Uddin 2000).

For simple use, George and Uddin (2000) also provided direct one-to-one relationships for both coarse- and fine-grained soils for the same parameters. The following relationships were developed from their field studies (Equation 8 for coarse-grained and Equation 9 for fine-grained soils):

$$M_R \text{ in MPa} = 235.3 \times \text{DCPI}^{-0.48} \quad (8)$$

$$M_R \text{ in MPa} = 532.1 \times \text{DCPI}^{-0.49} \quad (9)$$

Abu-Farsakh et al. (2004) studies also focused on the DCP device for determining moduli properties of Louisiana subsoils. Experimental and field investigations are already explained in the previous sections. Figure 69 shows two DCP tests conducted on the identical subgrade material specimen in laboratory conditions, and these results show that the DCP provides repeatable results.

The regression analysis, which was conducted to find the best correlation between the M_{FWD} in MPa and the DCP parameter, penetration ratio (PR) in millimeters per blow, yielded a nonlinear regression model presented in Equation 10:

$$\ln M_{\text{FWD}} = 2.35 + [5.21 / \ln \text{PR}] \quad (10)$$

The R^2 value for this correlation is 0.91, indicating a good correlation. Figure 70 presents comparisons between the developed correlation predictions along with the raw test data as well as other available models in the literature.

Edil and Benson (2005) reported several correlations composed of DCP parameters and GeoGauge SSG parameters (see Figure 71). No direct relationships were developed between DCP parameters and the resilient moduli; however, moduli can be approximated based on GeoGauge stiffness parameters.

Edil and Benson (2005) determined correlation coefficients in their regression analysis. This study also showed the potential use of DCP to address compaction quality of the subgrades. The normalized DCP parameter with respect to compaction moisture contents was correlated with the relative compaction of the subgrades (see results in Figure 72). The normalized parameters were close to 0 for the majority of the compacted subgrade and varied between −200 and 150 for uncompacted subgrades. These results show that the DCP can be utilized for compaction quality assessments of subgrades. Other studies by Amini (2003) and Zhang et al. (2004) reported similar DCP applications.

As part of the research performed for the Kansas DOT, Chen et al. (1999) conducted DCP and FWD tests on six pavements. EVERCALC was used for backcalculating the

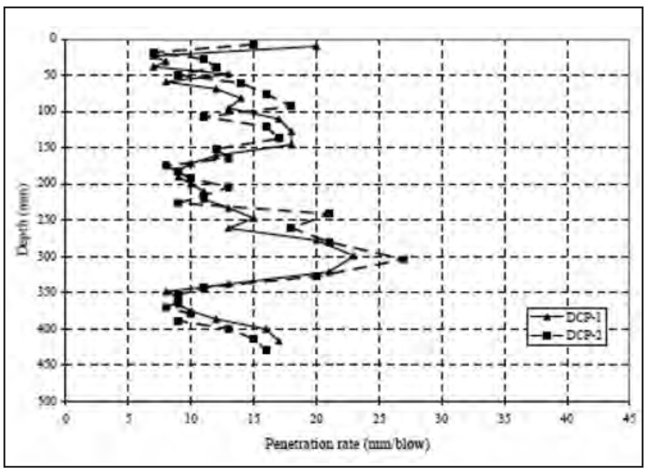


FIGURE 69 DCP tests on compacted material (Abu-Farsakh et al. 2004).

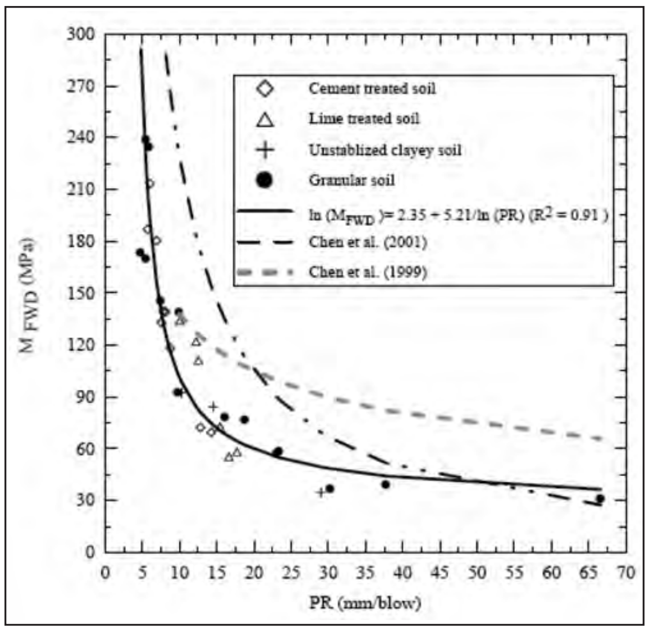


FIGURE 70 Comparisons between backcalculated moduli from DCP correlation (Abu-Farsakh et al. 2004).

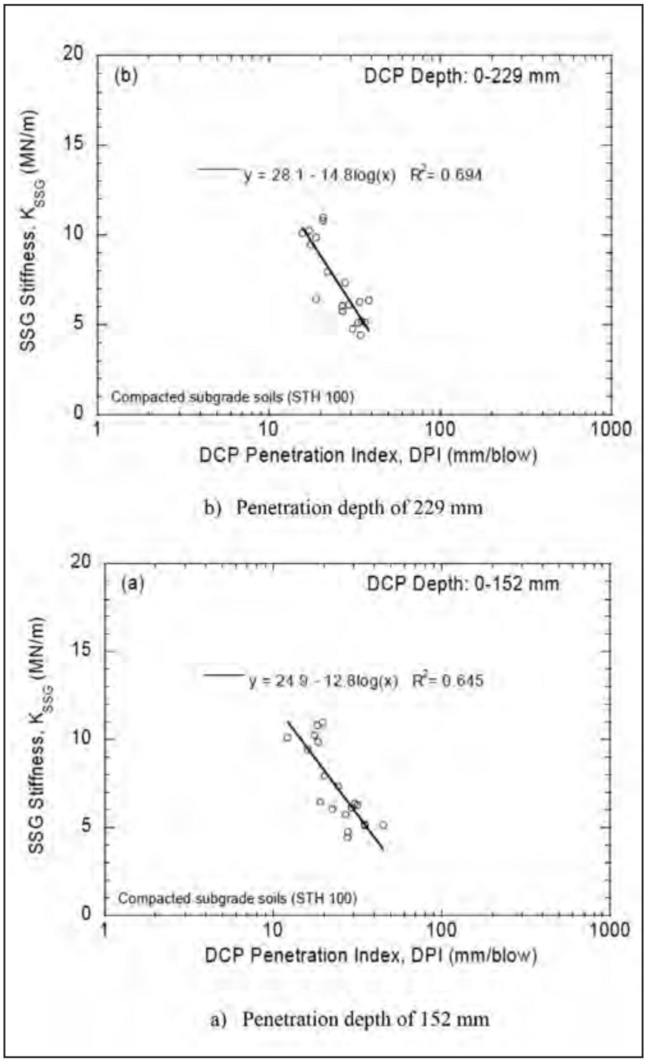


FIGURE 71 Correlations between DCP parameters and SSG stiffness properties of compacted subgrades (Edil and Benson 2005).

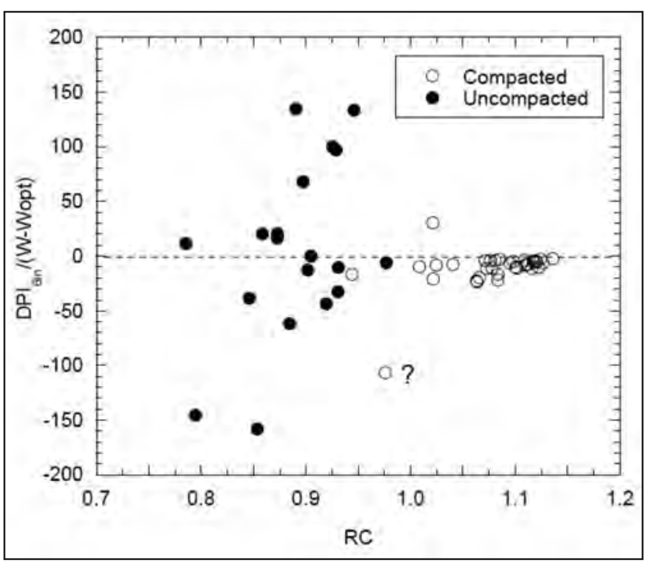


FIGURE 72 Correlations between normalized DCP parameter with relative compaction (RC) of the subgrades (Edil and Benson 2005).

stiffness of subgrades. The following correlation was developed between backcalculated moduli or stiffness of subgrade and the DCP parameter, DCPI in millimeters:

$$M_R \text{ (ksi)} = 338 \times \text{DCPI}^{-0.39} \quad (11)$$

where DCPI is expressed in millimeters per blow. The R^2 of 0.42 is obtained for this correlation.

Chen et al. (2001) used CBR DCP parameter-based indirect correlations to estimate the moduli from DCP results of field sections used for TxDOT accelerated loading-related tests. The predicted moduli are comparable with those calculated from maximum dry density measurements under FWD tests. This study reported that the laboratory-determined subgrade soil moduli were slightly higher than the estimated moduli from the DCP-based indirect correlations. The factor of 0.33 currently recommended by the 1993 AASHTO design guide to convert backcalculated modulus to laboratory resilient modulus is not applicable to the data measured by Chen et al. (2001).

Chen et al. (2007) developed new equations based on their test data for both base and subgrade soils. The equation is of the following form:

$$M_R \text{ (ksi)} = 78.05 \times \text{DPI}^{-0.67} \quad (12)$$

where DPI is measured in millimeters per blow.

Nazarian et al. (1996) used DCP on aggregate bases to measure the DCPI values. Figure 73 presents the DCP results at different elevations of the base layer. This research has not addressed the use of DCP to determine the modulus as the equations used are empirical in nature. The results in the figure show the transitions from layer to layer.

The MnDOT supported several new studies addressing the use of DCP to assess compaction quality to determine the moduli of pavement layers. Dai and Kremer (2006) and Petersen and Petersen (2006) assessed the newly developed

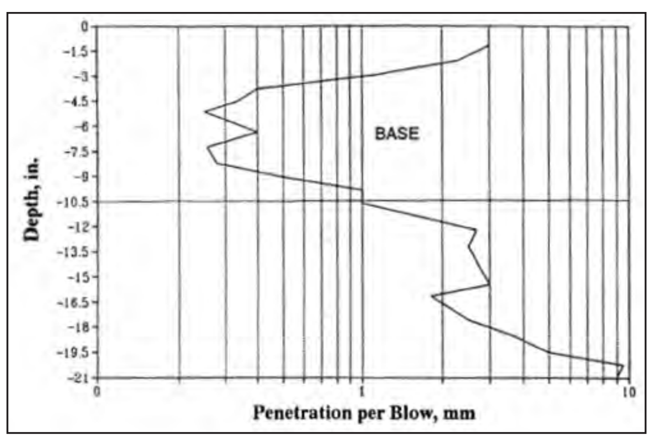


FIGURE 73 DCP results on a base layer (Nazarian et al. 1996).

DCP-based specifications for addressing the construction of compacted subgrades and bases as well as the potential use of the DCP in place of sand cones to evaluate the relative densities of the granular fills. The overall feedback from the field inspectors was positive.

FIGURE 74 presents the moduli interpreted from DCP and other devices for a site subjected to intelligent compaction. The DCP correlation used to determine the modulus (E_{DCP}, which is similar to backcalculated FWD or LWD stiffness values) follows:

$$\text{Log}\,(E_{DCP}) = 3.05 - 1.06 \times \log\,(\text{DCP}) \qquad (13)$$

where DCP is measured in millimeters per blow.

In summary, the DCP device has been used by different agencies for years to estimate the moduli of compacted subgrades and granular soils. Other applications of this device include compaction QC/QA tests and determination of layering by studying the slope variations in the DCP profiles. The majority of the correlations developed for resilient modulus are site specific and empirical in nature and hence their use for soils other than those used in the studies requires a careful examination and engineering judgment.

Quasi-Static Cone Penetrometer

Cone penetration tests (CPTs) provide two independently measured parameters, cone tip resistance (q_c) and cone frictional resistance (f_s). Another independent parameter is the total pore pressures (u_t) at one or more locations, which are measured when the cone penetrometer is fitted with piezometers. Figure 75 shows a piezocone device. All these measured

FIGURE 75 Piezocone penetrometer.

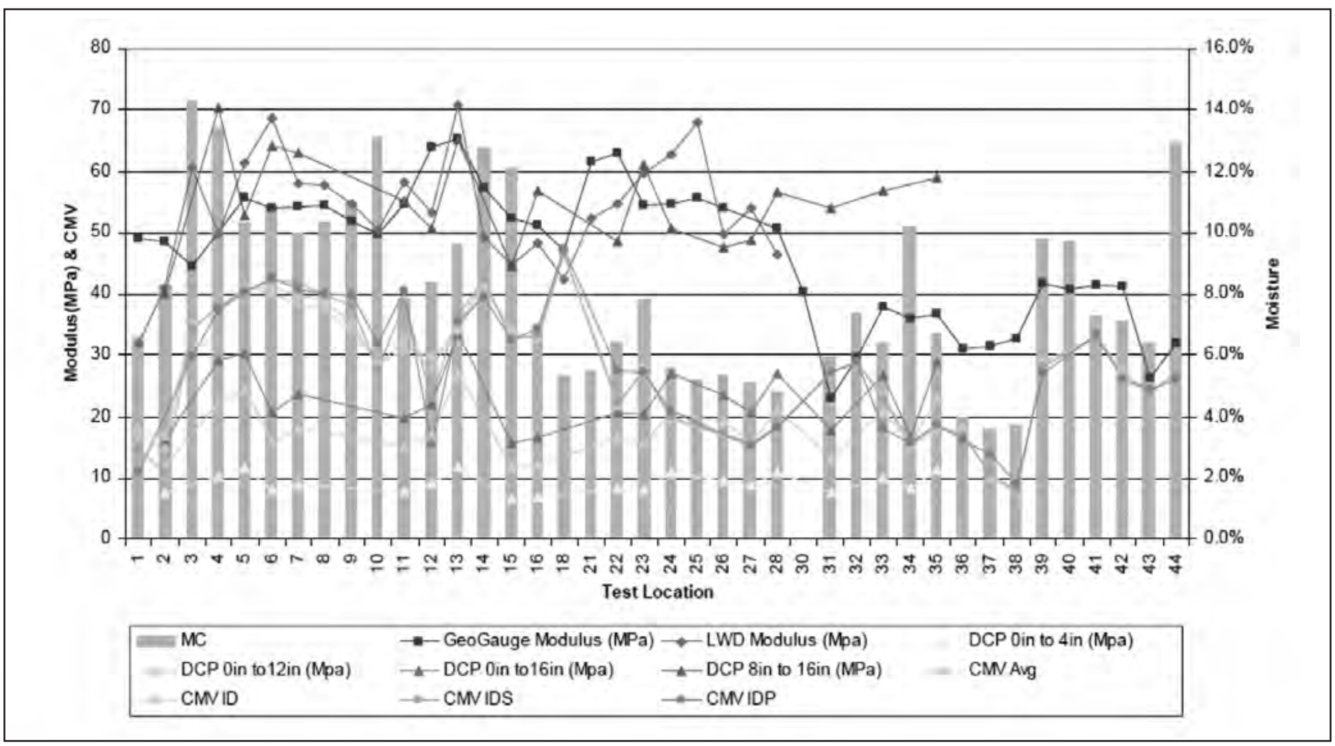


FIGURE 74 Moduli interpreted by DCP and comparisons with other moduli (Petersen and Peterson 2006).

parameters, upon various corrections and modifications, can be used to classify soil strata and interpret various properties of the stratified soils. Several classification and interpretation charts are already available in the literature (a summary can be found in Meigh 1987).

Resilient Moduli Interpretations by Cone Penetration Tests

Mohammad et al. (2000, 2002, 2007; Gudishala 2004) present the results of a research investigation in which CPT soundings were used to predict the resilient modulus of subgrade soils. Field and laboratory testing programs were carried out on two types of cohesive soils. CPT soundings were performed using two types of cones: large and miniature CPT devices with cross-sectional areas of 15 cm^2 and 2 cm^2. Figure 76 presents CPT results obtained on sites containing heavy clay material. Resilient modulus tests were also conducted on both clays, and these results along with the CPT results were statistically analyzed.

Resilient modulus results of clays at various stress conditions in the laboratory are used to determine realistic moduli that are representative of the stress conditions under a traffic single-wheel loading of 20 kN. ELSYM5 was used for the stress analysis. Based on statistical analyses, two correlation models were proposed to estimate the resilient modulus from the CPT data and basic soil properties. The first one is valid for in situ subgrade conditions and the second one is valid for overburden and traffic conditions. Equation 14 is derived for overburden conditions and Equation 15 is for overburden and traffic conditions:

$$\frac{M_R}{\sigma_c^{0.55}} = \frac{1}{\sigma_v}\left(31.8\times q_c + 74.8\times\frac{f_s}{w}\right) + 4.08\times\frac{\gamma_d}{\gamma_w} \quad (14)$$

$$\frac{M_R}{\sigma_3^{0.55}} = \frac{1}{\sigma_1}\left(47.0\times q_c + 170.4\times\frac{f_s}{w}\right) + 1.70\times\frac{\gamma_d}{\gamma_w} \quad (15)$$

where M_R is the resilient modulus (MPa), q_c is the cone resistance (MPa), f_s is the sleeve friction (MPa), σ_c or σ_3 is the confining stress (kPa), σ_v is the vertical stress (kPa), w is the water content in decimal number format, γ_d is the dry unit weight (kN/m^3), and γ_w is the unit weight of water

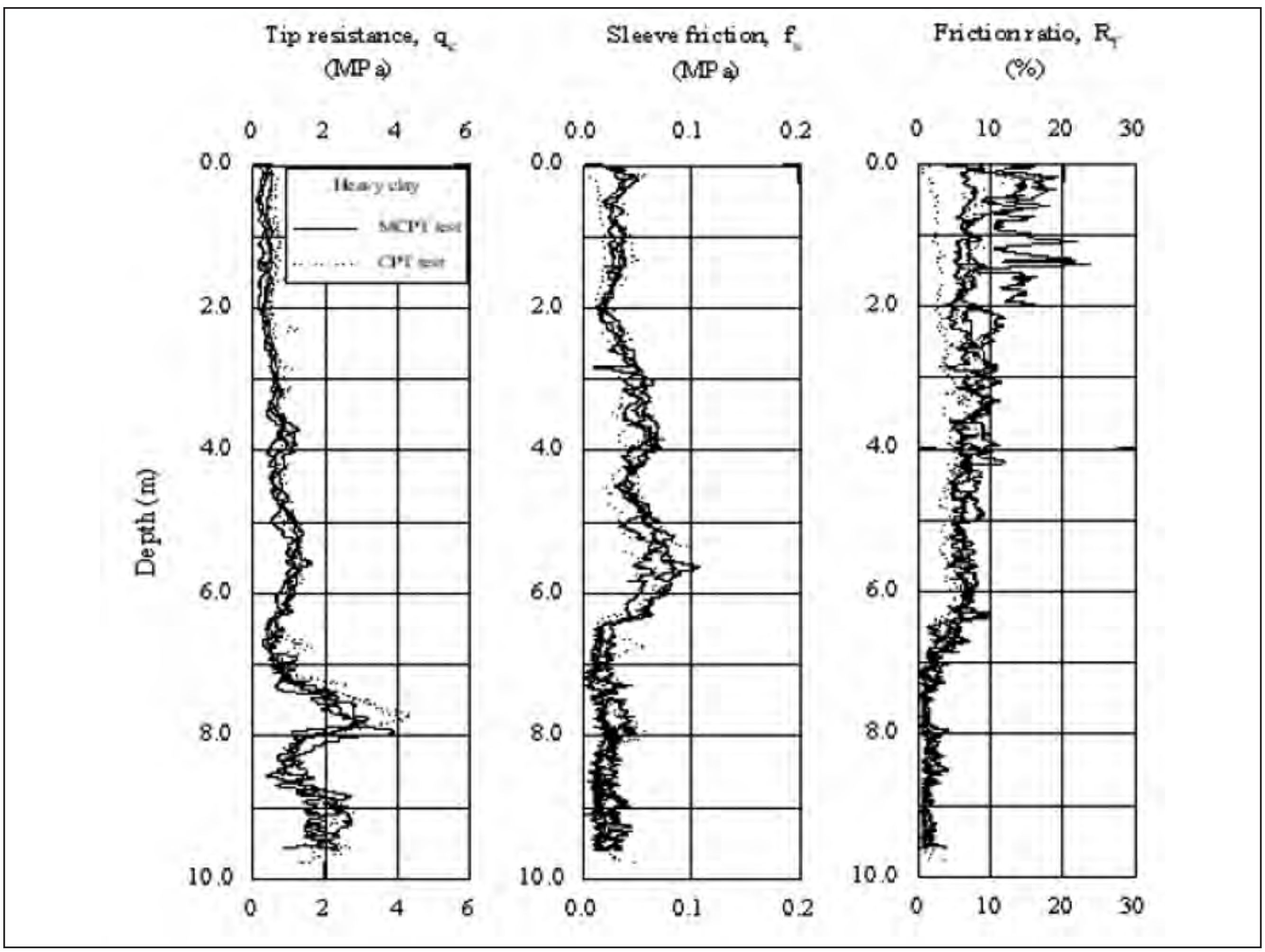


FIGURE 76 CPT results on heavy clay (Mohammad et al. 2000).

(kN/m³). The coefficients of determination values for both equations are reported as 0.99.

Figure 77 shows the predictions of the above model and the resilient moduli measurements for various site subgrades. The authors reported that a good agreement between predicted and measured moduli of cohesive subgrades was obtained (Mohammad et al. 2000). These correlations are developed for silty clay and heavy clayey soils, and hence they are valid for such soils only. Another set of correlations for coarse soils was separately developed for coarse-grained materials for both overburden and combined overburden and traffic conditions (Mohammad et al. 2000).

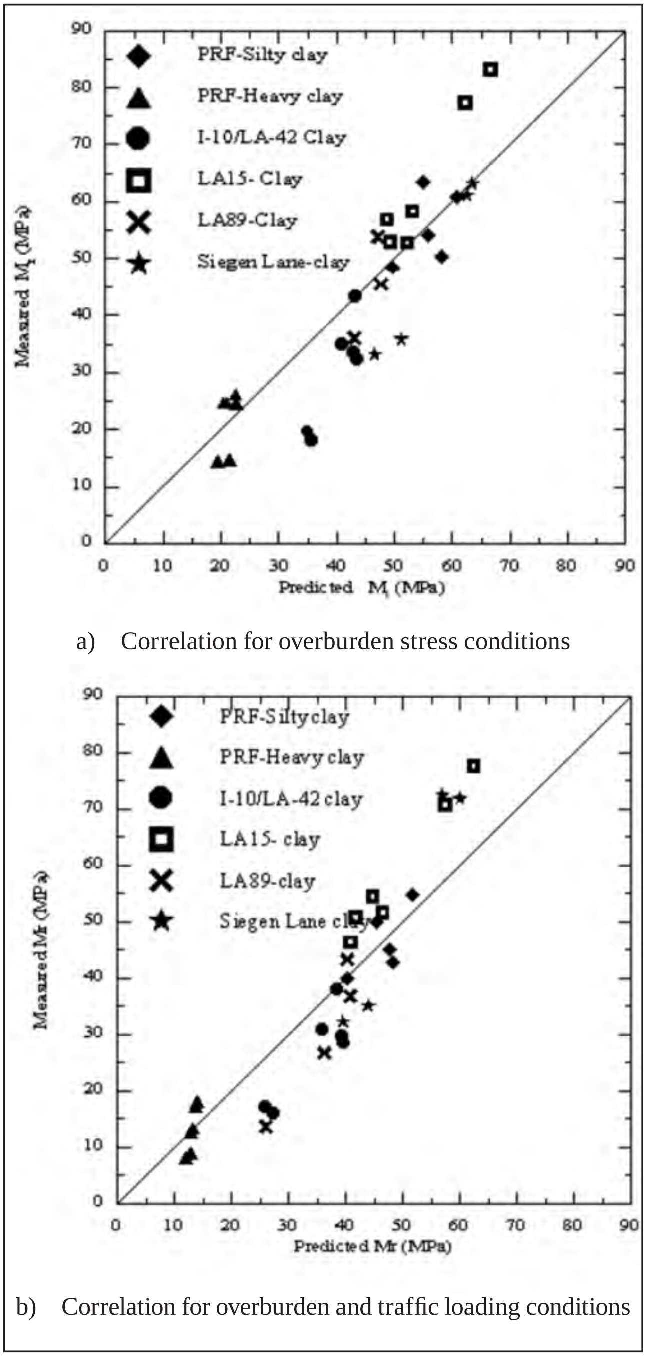


FIGURE 77 Resilient moduli predictions by CPT models and measurements by repeated load triaxial tests (Mohammad et al. 2000).

Pressuremeter

The following section provides detailed descriptions and operation details of pressuremeters (PMTs) used for resilient moduli predictions. Figure 78 presents a typical schematic of a TEXAM PMT device.

Typically, this test is performed either in stress-controlled or strain-controlled environments. In stress-controlled conditions, applied pressure is increased on the membrane and the corresponding displacements are monitored. In strain-controlled tests, the rate of expansion of the membrane is controlled by the use of volumetric increments through liquid-filled PMTs. In these tests, the corresponding pressures resulting from constant volume increments are monitored. The measured pressure–strain profiles from these tests can be used to determine in situ strength and compressibility characteristics, including stiffness properties. Figure 79 presents the procedure adopted by Cosentino and Chen (1991) for determining the resilient modulus of subgrades.

Based on the method of installation, PMTs can be classified into prebored PMTs, self-bored PMTs, and push-in

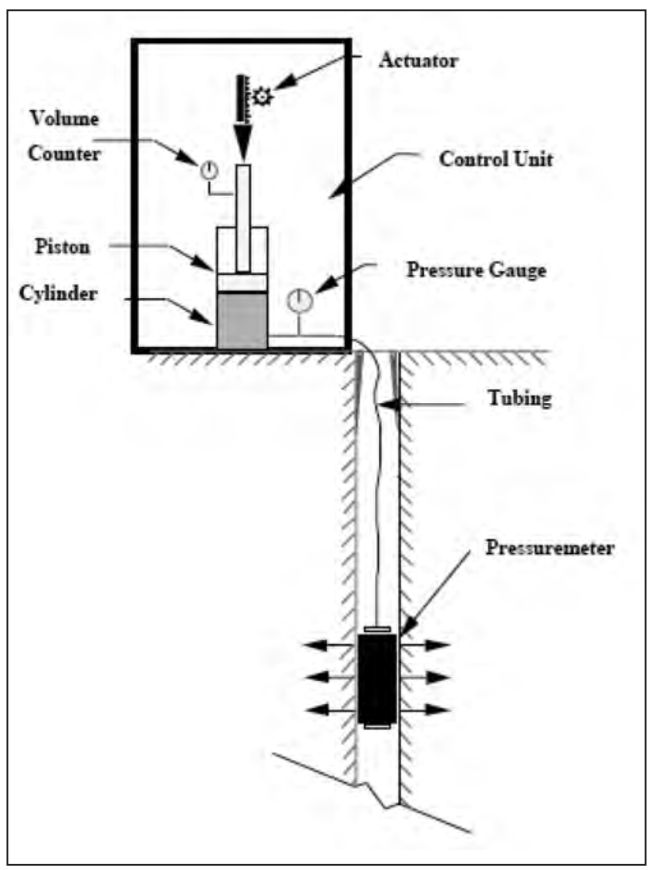


FIGURE 78 TEXAM pressuremeter (Cosentino et al. 2006).

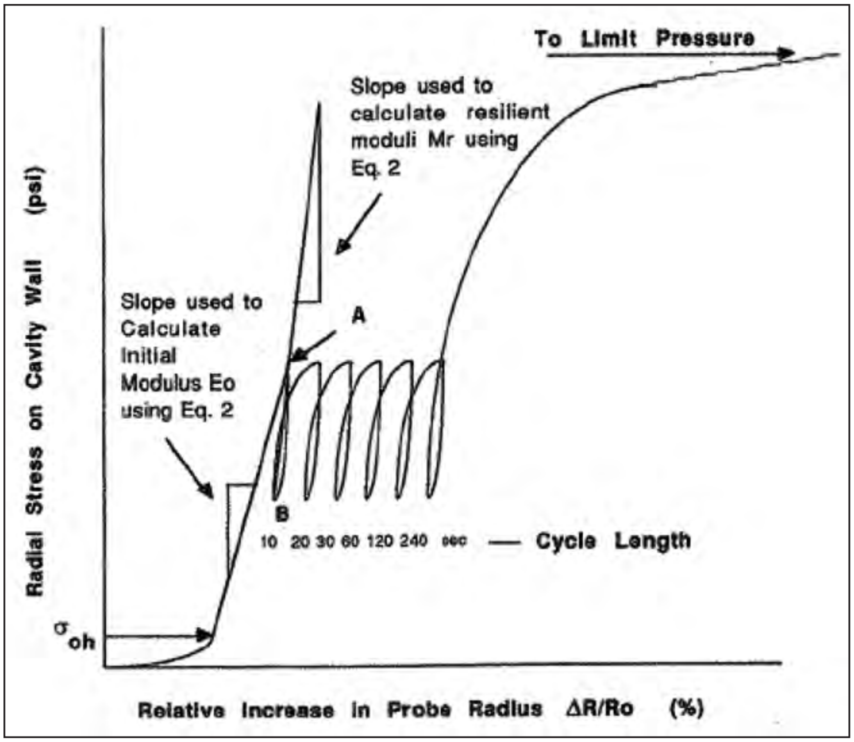


FIGURE 79 Resilient moduli measurements from radial stress—strain profile (Cosentino and Chen 1991).

PMTs. Prebored PMTs are lowered into a soil pocket that is bored especially for the test. Self-bored PMTs, such as the Cambridge Self-boring Pressuremeter, create their own pockets for tests. Push-in or displacement PMTs, such as cone pressuremeters, are either pushed or driven into various elevations for testing.

The special PMT test called the resilient modulus PMT test was developed to enable six resilient moduli to be determined from six unload–reload cycles conducted for various load durations along the linear portion of the in situ stress–strain response. The various cycle lengths enabled the resilient moduli to be determined as a function of the load durations typically encountered during the traffic loading of a pavement. The cycle lengths used were 10, 20, 30, 60, 120, and 240 s. The duration of the whole test after the preboring operation is 17 minutes.

To increase the usefulness of the PMT in the area of pavement design and evaluation, resilient moduli (determined from a special PMT test) were correlated to CBR test results (Cosentino and Chen 1991). The PMT resilient moduli-CBR correlations developed based on 30, 60, and 120 s cycle lengths compared well with the existing resilient moduli–CBR correlations measured from 0.1 s cycles. Another study conducted by Nelson et al. (2004) reported the use of PMT for estimating the moduli of backfill material. The intent of this study was to address the compaction quality of a backfill material of a retaining wall. Based on 15 PMTs, the moduli of subgrades is 26 MPa with a standard deviation of 7 MPa.

Major advantages of PMTs are that they are performed in situ and hence no soil sampling is needed. One reason for an insufficient number of research studies performed on PMTs is the need for trained individuals to perform the PMT testing. However, advances in instrumentation and the development of new PMT probes make these devices more attractive for performing in situ studies in the field in a quick and efficient manner. New PMTs including Pencel PMTs (PPMTs) can be used in shallow subgrades either by pushing or by driving. Sophisticated instrumentation in the PPMTs makes them more attractive for pavement moduli evaluation studies.

Plate Load Test

Plate load tests (PLTs) were used for resilient moduli interpretations and a few states, including Florida and Louisiana, have attempted to use them for correlating with the resilient modulus of subgrades (Abu-Farskh et al. 2003). The PLT operations involve loading a circular plate that is in contact with the layer to be tested and measuring the deflections under load increments. Circular plates usually 30 cm (12 in.) in diameter are generally used and the loading is transmitted to the plates by a hydraulic jack.

During the test, a load-deformation curve will be recorded and these data will be used to estimate the moduli of the load—deformation or stress—strain plot, which is referred to as E_{PLT}. If the field test is performed in cyclic mode, then the slope of the stress–strain curve provides the moduli. The moduli measured from this test are regarded as a composite moduli as the depth of influence is considered to extend more than one layer (Abu-Farskh et al. 2003). Nelson et al. (2004) also reported the use of PLTs to estimate the moduli of compacted retaining wall backfill material. Though the PLT method is primarily used for rigid pavements, several researchers have attempted to correlate the moduli with the elastic moduli of the subgrades. More research is still needed to better understand the applicability of this method in evaluating the resilient properties of subgrades and bases.

Dilatometer

Another in situ intrusive device known as a dilatometer (DMT) has been used to de termine the resilient moduli properties of subgrade soils. Borden et al. (1986) noted the unique relationship between the resilient modulus and dilatometer modulus, a parameter measured from field

DMT test data. Similar correlations were also obtained between DMT moduli and initial tangent moduli. Borden et al. (1986) suggested the need for additional research to validate these relationships. No other resilient moduli studies utilizing DMTs in the United States were documented in the literature.

SUMMARY

The previous sections provide comprehensive details of various in situ methods to determine the resilient moduli properties of subgrades and bases.

- The majority of the intrusive equipment is used for the interpretation of resilient moduli of subgrades that include both coarse-grained, fine-grained, and mixed soils. DCP is the most prominently used in situ intrusive device, and it has been used by several DOTs for compaction QC/QA tests of bases and subgrades and determination of layer moduli. More than 50% of the state DOTs used this device for the previously mentioned applications.
- Correlations that use DCPs are empirical and site specific. Their use for other sites requires considerable engineering judgment.
- Soil-specific correlations are not developed for predicting the resilient moduli properties. However, the use of DCP correlations should be carefully considered because the configurations of these devices are not standardized in the highway engineering community. ASTM recently standardized the DCP method in ASTM D6951-03 for shallow pavement applications, and hence the use of the standardized DCP device will result in a reliable DCP test database.
- Quasi-static cone penetrometer test has been used in one study, which revealed the potential of this method to predict the resilient properties of cohesive subgrades. Though good correlation was obtained between CPT and M_R results, this correlation requires further validation with the results from clayey soils other than those used in the research.
- PMT, DMT, and PLT have been sparingly used for the estimation of resilient properties. The results from these studies are good to promising. No additional studies are reported, however, probably because of high costs and lengthy time of operations as well as training of operators to perform these tests on a routine basis. With the advances in instrumentation and automation, these methods could become attractive and practical for pavement subgrade exploration and in situ evaluation of resilient properties.

CHAPTER FIVE

CORRELATIONS AND MATRIX TABLES

RESILIENT MODULI CORRELATIONS

Different types of correlations are used to estimate the resilient properties of subgrades and bases. Several literature sources were collected that provided comprehensive details of these models and correlations. The following sections are prepared based on the information available in these reports. Currently, two approaches are followed to analyze resilient moduli test data. One of them is to develop relationships between resilient moduli values and various soil properties or different in situ test-related parameters. Statistical regression tools are usually adopted for this exercise.

The other one is to analyze the resilient moduli data with a formulation that accounts for confining or deviatoric or both stress forms. This formulation usually contains several model constant parameters. Once these parameters are determined, they are correlated with different sets of soil properties. These correlations are termed here as semi-empirical or indirect correlations. The next few sections cover some of the correlations currently used in the resilient moduli modeling.

DIRECT RESILIENT MODULI CORRELATIONS

In the direct correlations, two types of correlations were reported in the literature. The first correlates resilient moduli directly with the soil properties. The second correlates the moduli with in situ test parameters. Both types are frequently used by pavement design engineers. Because there are several models, this section associates these models with simple terminology for quick identification.

In the case of direct correlation of resilient modulus with soil properties, the abbreviation MRDS (MR stands for Resilient Modulus and DS stands for Direct Correlations and Soil Properties–Based Relationship) is used. For in situ-based correlations, the abbreviation MRDI (MR stands for Resilient Modulus and DI stands for Direct and In Situ Test–Based Relationship) is used.

Direct and Soil Property–Based Models

In the following section, several direct models from the literature are presented. The development of these correlations was based primarily on multiple linear regression tools. Such practice sometimes results in correlations with attributes that do not follow physical or practical expected trends. For example, in MRDS 7, the stiffness of a soil decreases with an increase in dry unit weight. Users should evaluate the use of any select correlations with the local soil test database before routine use.

MRDS 1

The following model defining resilient modulus as a function of degree of saturation and compaction moisture content was developed by Jones and Witczak (1972):

$$\text{Log } M_R \text{ (ksi)} = -0.111w + 0.0217S + 1.179 \tag{16}$$

where w is the compaction moisture content in percent and S is degree of saturation in percent. The R^2 value of this equation is 0.44. This equation is valid for clays (A-7-6 type), because the model correlation was developed primarily using the same types of clayey samples from California. The M_R of clays used in this correlation was determined from RLT tests on clay samples under a maximum cyclic deviator stress of 6 psi and a confining pressure of 2 psi.

MRDS 2

Thompson and Robnett (1979) studied the resilient characteristics of several Illinois fine-grained subgrade soils described in the earlier sections. Resilient modulus test results at a deviatoric stress of 6 psi and zero confining pressure are then correlated with soil characteristics. The following correlation has a coefficient of determination, R^2 of 0.80, suggesting a good correlation obtained for the Illinois subgrades. The equation follows:

$$M_R\text{(ksi)} = 6.37 + 0.034\times\%\text{CLAY} + 0.45\times\text{PI} - 0.0038\times\%\text{SILT} - 0.244\times\text{CLASS} \tag{17}$$

where M_R is resilient modulus measured at $\sigma_d = 6$ psi for soils with a relative compaction of 95% as per AASHTO T99; %CLAY is clay content in percent; PI is plasticity index in percent; %SILT is silt content in percent; and CLASS is AASHTO classification (for A7-6 soils, use 7.6 in the expression). This model is valid for cohesive soils and does not address stress effects.

Thompson and LaGrow (1988) developed the following correlation for the compacted subgrades of Illinois:

$$M_R\,(psi) = 4.46 + 0.098 \times C + 0.12 \times \mathrm{PI} \tag{18}$$

where C is percent clay and PI is the plasticity index. They proposed the following correction factors for moisture susceptibility, which need to be applied to the estimated resilient moduli. For clay, silty clay, and silty clay loam, the correction factor is 0.7; for clay loam, the correction factor is 1.5.

MRDS 3

Several models based on CBR, R value, were introduced in the mid-1980s and a list of these including a few recommended by the AASHTO design guide are presented here. The Asphalt Institute (1982) recommended the following relationship (Equation 19) between resilient modulus and R value:

$$M_R\,(psi) = A + B \times R \tag{19}$$

where A is constant and varies from 772 to 1,155; B is constant and varies from 369 to 555; and R is R value (AASHTO T190). For fine-grained soils whose R values are less than or equal to 20, the 1993 AASHTO guide recommends A is 1,000 and B is 555.

Buu (1980) reported the following relationship for fine-grained Idaho soils with R values greater than 20. This correlation is valid for σ_d = 6 psi and σ_3 = 2 psi.

$$M_R\,(ksi) = 1.6 + 0.038 \times R \tag{20}$$

MRDS 4

Both CBR and unconfined compression strength–based correlations are presented in the following. One of the earlier equations, developed by Heukelom and Klomp (1962), provided a relationship between resilient modulus and CBR value and has been recommended by several AASHTO design guides. This relationship follows:

$$M_R\,(psi) = 1500 \times CBR \tag{21}$$

The lower and upper bound values of the constant of proportionality ranged between 750 and 3,000, respectively. This equation provides reasonable estimates of resilient modulus for fine-grained soils with a CBR value of 10 or less. Other M_R correlations are given here:

$$M_R\,(ksi) = 0.86 + 0.31 \times q_u \tag{22}$$

(Thompson and Robnett 1979)

$$M_R\,(psi) = 2554 \times \mathrm{CBR}^{0.64} \quad \text{(Powell et al. 1984)} \tag{23}$$

$$M_R\,(MPa) = 10.3 \times \mathrm{CBR} \quad \text{(Asphalt Institute 1982)} \tag{24}$$

$$M_R = a \times S_{u,1\%} \quad \text{(Lee et al. 1997)} \tag{25}$$

where q_u is unconfined compression strength. Equation 25 was developed based on the resilient modulus test database compiled from testing the subgrades from Indiana. $S_{u,1\%}$ is undrained shear strength at 1% axial strain and a is the constant determined from Figure 80.

Several state DOTs formulated their own procedures for determining the resilient modulus of compacted subgrades. The following procedure describes the steps followed by the Ohio DOT for predicting the resilient properties of their subgrades. It uses the following M_R–CBR relationship, where CBR is estimated in two steps. The first step is to estimate the group index (GI) from basic soil properties (Figure 81*a*) and the second step is to correlate CBR with the GI parameter determined in step 1 (Figure 81*b*):

$$M_R\,(psi) = 1200 \times \mathrm{CBR} \tag{26}$$

MRDS 5

The following model was developed by Carmichael and Stewart (1985), which is based on a large database of resilient moduli test results. The formulation of this expression follows:

$$\begin{aligned} M_r\,(ksi) &= 37.4 - 0.45 \times \mathrm{PI} - 0.62 \times w \\ &- 0.14 \times S200 + 0.18 \times \sigma_3 - 0.32 \times \sigma_d \\ &+ 36.4 \times CH + 17.1 \times MH \end{aligned} \tag{27}$$

where *CH* is 1 for CH soil, 0 otherwise; *MH* is 1 for MH soil, 0 otherwise; *S*200 is percent passing #200 sieve (%). The coefficient of determination R^2 value is 0.80, suggesting that this is a good correlation. This correlation is valid for subgrade soils containing clays and silts.

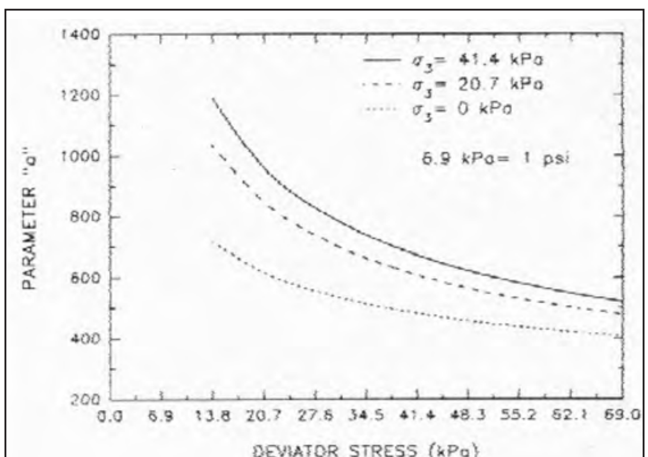
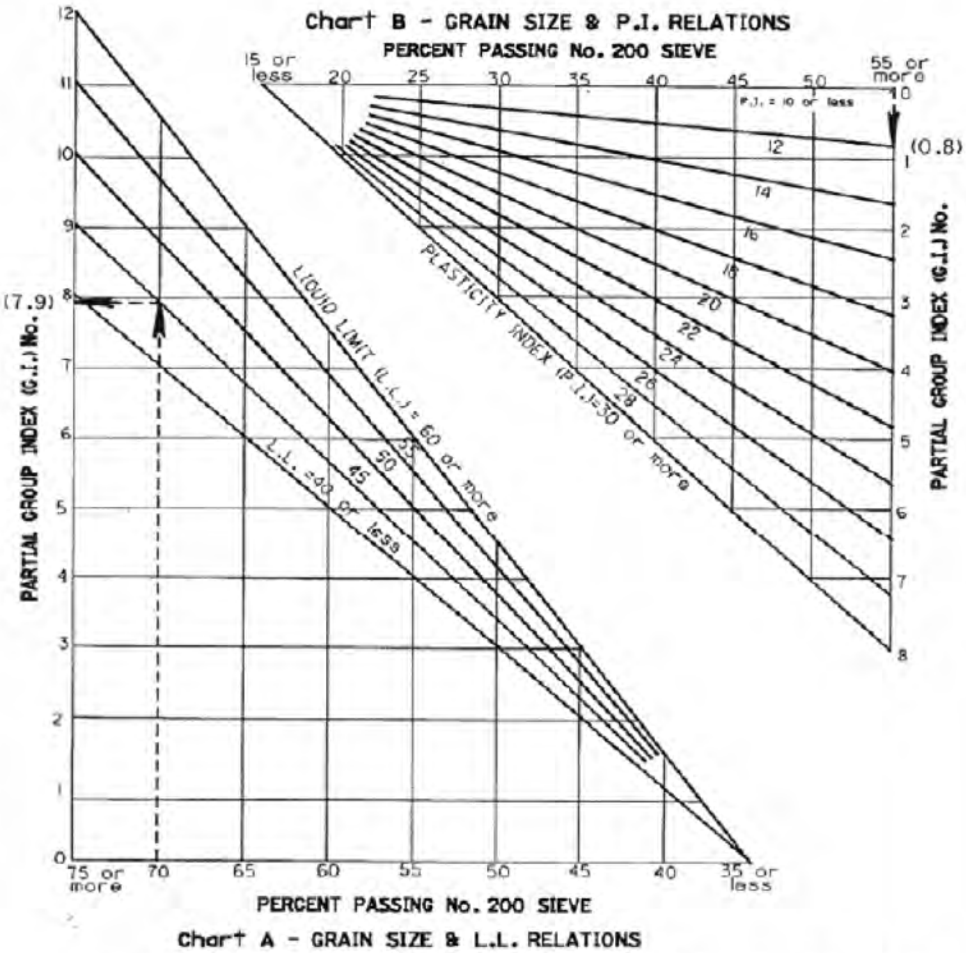
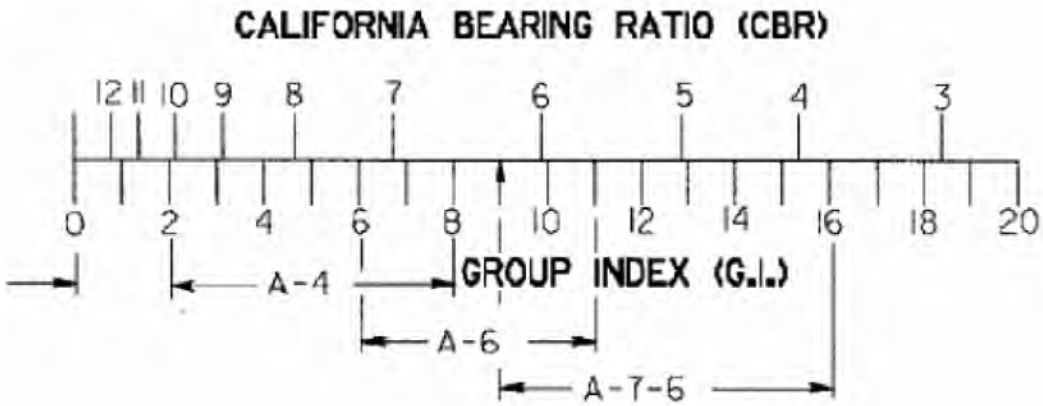


FIGURE 80 ‘a’ parameter for M_R prediction (Lee et al. 1997).



a) Group index determination based on soil size and LL



b) GI–CBR correlation

FIGURE 81 Correlations to predict resilient modulus using CBR and soil support values (Ohio DOT 1999).

Carmichael and Stewart (1985) also proposed a separate correlation for granular soils and base aggregates:

$$\log M_R(ksi) = 0.523 - 0.0225 \times \%W + 0.544 \times \log\theta + 0.173 \times SM + 0.197 \times GR \quad (28)$$

where $\%W$ is compaction moisture content; θ is bulk stress in psi; SM is 1 for SM soil and 0 for other soils; and GR is 1 for gravelly soils (GM, GW, GC, and GP) and is 0 for other soils.

MRDS 6

Elliott et al. (1988) tested several Arkansas soils and developed the following two resilient modulus models at two different deviator stresses of 4 and 8 psi:

At σ_d = 4 psi:

$$M_R \text{ (ksi)} = 11.21 + 0.17\%\text{CLAY} + 0.20\text{PI} - 0.73w_{\text{opt}} \quad (29)$$

At σ_d = 8 psi:

$$M_R \text{ (ksi)} = 9.81 + 0.13\%\text{CLAY} + 0.16\text{PI} - 0.60w_{\text{opt}} \quad (30)$$

The coefficients of determination for Equations 29 and 30 were 0.80 and 0.77, respectively. The resilient moduli determined from these relationships are valid for the above stresses. This relationship is valid for cohesive subgrades.

MRDS 7

Drumm et al. (1990) tested several fine-grained soils from different parts of Tennessee and test data were used to develop the following direct relationships for resilient modulus. The first of these two relationships presents breakpoint resilient modulus:

$$M_{ri}(ksi) = 45.8 + \frac{0.00052}{a} + 0.19 \times q_u + 0.45 \times \text{PI} - 0.22 \times \gamma_d - 0.25 \times S - 0.15 \times S_{200} \quad (31)$$

where M_{ri} is the breakpoint resilient modulus, which assumes that the resilient modulus versus deviator stress relationship is bilinear, and M_{ri} represents the intersection of the bilinear plot; a is initial tangent modulus (psi) of a stress–strain curve from unconfined compression tests; q_u is unconfined compressive strength (psi); PI is plasticity index (%); γ_d is dry unit weight (pcf); S is degree of saturation (%); and S_{200} is percent passing the #200 sieve. The coefficient of determination (R^2) for the breakpoint resilient modulus correlation was 0.83. Figure 82 presents the definitions of moduli parameters; a and b are determined from this relationship.

The second correlation introduces a hyperbolic relationship for the determination of resilient modulus, and the constants used in this correlation are defined as functions of various soil properties:

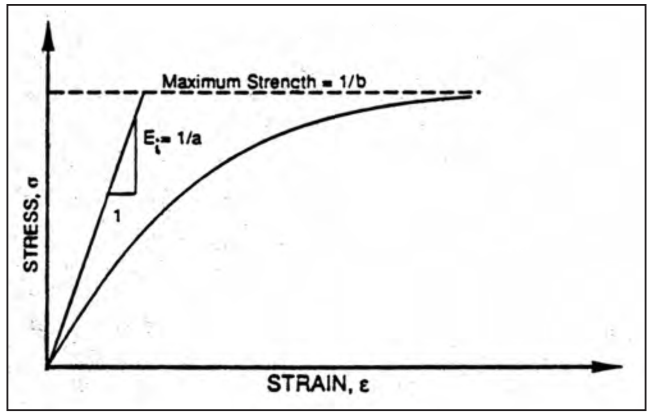


FIGURE 82 Hyperbolic model and definitions of model constants (Drumm et al. 1990).

$$M_r(ksi) = \frac{a' + b'\sigma_d}{\sigma_d} \quad (32)$$

where

$$a' = 318.2 + 0.377 \times q_u + 0.73 \times \%\text{CLAY} + 2.26 \times \text{PI} - 0.92 \times \gamma_d - 2.19 \times S - 0.30 \times S_{200}$$

$$b' = 2.10 + \frac{0.00039}{a} + 0.104 \times q_u + 0.09 \times LL - 0.10 \times S_{200};$$

%CLAY is percent finer than 0.002 mm; and LL is liquid limit (%). The coefficient of determination of this expression is 0.80.

This model adequately predicts resilient moduli for Tennessee subgrades containing predominantly cohesive soils and subjected to a wider range of deviator stresses applied to them. The above resilient moduli models yield resilient modulus at zero confining stress only.

MRDS 8

The Farrar and Turner (1991) correlation was developed based on the resilient properties measured on 13 subgrade materials from Wyoming.

$$M_R(psi) = 30280 - 359 \times S - 325 \times \sigma_d + 237 \times \sigma_c + 86 \times PI + 107 \times S_{200} \quad (33)$$

The coefficient of determination (R^2) for this correlation was 0.663, and this expression is recommended for fine-grained subgrades.

MRDS 9

Several resilient modulus tests were performed on eight Tennessee subgrade soils composed of A4 through A7-6 types (Hudson et al. 1994). Based on the tests, the following model was proposed for the estimation of resilient modulus:

$$\begin{aligned}\log\ M_R(psi) &= 46.93 + 0.018\times\sigma_d + 0.033\times\Delta\gamma_d \\ &- 0.114\times LI + 0.468\times S + 0.0085\times \text{CLASS}^2 \\ &- 0.0033\Delta w^2 - 0.0012\times\sigma_c^2 + 0.0001\times PL^2 \\ &- 0.0278\times LI^2 - 0.0017\times S^2 - 38.44\times\log S \\ &- 0.2222\times\log\sigma_d\end{aligned} \tag{34}$$

where $\Delta\gamma d$ (pcf) is deviation from the Standard Proctor maximum dry density, which is $\gamma_d - \gamma_{\text{dmax}}$; LI is liquidity index (%); and Δw (%) is deviation from the optimum water content, w_{opt}, based on the Standard Proctor compaction tests. The coefficient of determination (R^2) was 0.70, and this expression is valid for cohesive subgrades.

MRDS 10

Li and Selig (1994) proposed the following expression for predicting the resilient modulus of fine-grained soils. To use this model, the modulus value at optimum moisture content should be known to users. Once it is known, the moduli at other moisture contents can be estimated using the following equation, which was developed based on a review of resilient modulus data obtained from soils throughout the United States. The equation for resilient modulus along paths of constant dry density but at different compactive efforts follows:

$$R_{m1} = 0.98 - 0.28\times\Delta w + 0.29\times\Delta w^2 \tag{35}$$

where R_{m1} is $M_R/M_{R\text{ opt}}$; $M_{R\text{ opt}}$ is the resilient modulus at the optimum water content; and change in moisture content is the difference between moisture content at which moduli are being estimated and optimum moisture content values. This equation is predominantly used for cohesive subgrades.

MRDS 11

Resilient modulus tests were performed on several subgrade samples from Texas by following SHRP Protocol P46 (Pezo and Hudson 1994). Based on the test database, the following resilient modulus prediction model was established, which requires six factors that gave the highest degree of correlation for these soils. The model is as follows:

$$M_R = F_0 \times F_1 \times F_2 \times F_3 \times F_4 \times F_5 \times F_6 \tag{36}$$

where F_0 is 9.80 ksi (English units) or 67.60 MPa (SI units); F_1 is the correction factor for moisture content; F_2 is the correction factor for relative compaction; F_3 is the correction factor for soil plasticity; F_4 is the correction factor for age of compacted specimen; F_5 is the correction factor for confining pressure; and F_6 is the correction factor for deviator stress. Values for the correction factors are presented in Table 11.

TABLE 11
CORRECTION FACTORS FOR THE RESILIENT MODULUS MODEL (PEZO AND HUDSON 1994)

Moisture Content (%)	F_1	$\gamma_d/\gamma_{d\max}$ (%)	F_2
10	4.0	100	1.00
15	2.0	95	0.90
20	1.0	90	0.80
25	0.5	85	0.70

Plasticity Index (%)	F_3	Sample Age (days)	F_4
10	1.00	2	1.00
20	1.50	10	1.10
30	2.00	20	1.15
≥40	2.50	≥30	1.20

σ_c (kPa/psi)	F_5	σ_d (kPa/psi)	F_6
13.8/2	1.00	13.8/2	1.00
27.6/4	1.05	27.6/4	0.98
41.4/6	1.10	41.4/6	0.96
		55.2/8	0.94
		69.0/10	0.92

The properties of the soils tested have the following ranges: moisture content from 10% to 35%; relative compaction from 80% to 100% based on AASHTO T99; plasticity index from 4% to 52%; compacted specimen age from 2 to 188 days; confining stress from 13.8 to 41.4 kPa (2 to 6 psi); and deviator stress from 11 to 102.8 kPa (1.6 to 14.9 psi). Factors such as AASHTO classification, seating pressures, and percent fines were also analyzed for the above resilient modulus correlation. However, these factors were not included in the correlation. The coefficient of determination for this model was 0.80 and the expression is valid for silty to clayey subgrades.

MRDS 12

Berg et al. (1996) conducted a study on one fine-grained and several coarse-grained Minnesota soils. The fine-grained soil was prepared at several different moisture contents but at a single dry density of about 110 pcf. The resilient modulus model developed from these test results is given in the following equation:

$$M_R(psi) = 1.518\times 10^{30}\left[f(S)\right]^{-13.85}\left[f(\sigma)\right]^{-0.272} \tag{37}$$

where $f(S)$ is saturation normalized by a unit saturation of 1.0%; $f(\sigma)$ is octahedral shear stress, τ_{oct}, normalized by a unit stress of 1.0 psi; and τ_{oct} is $(\sqrt{2}/3)\ \sigma_d$. The coefficient of determination (R^2) was 0.95, and the model is applicable to cohesive soils only.

MRDS 13

Gupta et al. (2007) proposed the following expression for resilient moduli prediction based on soil suction (ψ) measurements. This equation is valid for cohesive soil types tested in their research. The R^2 value of this correlation is 0.76, and the resilient modulus used in this expression is valid for a bulk stress of 83 kPa and an octahedral shear stress of 19.3 kPa.

$$M_R(kPa) = -54105 + 57898 \times \log \psi \tag{38}$$

Direct and In Situ Test–Based Models

MRDI 1 (DCP)

In the direct correlations, several DCP-based relationships are summarized in Table 12. More details on the use of these relationships are given in earlier sections. The terms including E_{DCP}, E, and M_{FWD} values are representative of stiffness measurements from nondestructive studies, whereas the resilient modulus (M_R) is derived from the RLT method. These relationships are mostly empirical in nature, and they are best applicable for the soils or soil types close to the ones from which these relationships are derived. Engineering judgment and local experience are prudent when using these models. Please note that these models are nondimensional and are unit sensitive.

MRDI 2 (CPT)

In the case of CPT-type correlations, Mohammad et al. (2000) formulated the following two correlations (Equations 39 and 40) for predicting the resilient properties of cohesive subgrades. The first expression is valid for overburden stress conditions and the second expression is valid for both overburden stress and traffic conditions.

$$\frac{M_R}{\sigma_c^{0.55}} = \frac{1}{\sigma_v}\left(31.8 \times q_c + 74.8 \times \frac{f_s}{w}\right) + 4.08 \times \frac{\gamma_d}{\gamma_w} \tag{39}$$

$$\frac{M_R}{\sigma_3^{0.55}} = \frac{1}{\sigma_1}\left(47.0 \times q_c + 170.4 \times \frac{f_s}{w}\right) + 1.70 \times \frac{\gamma_d}{\gamma_w} \tag{40}$$

where M_R is the resilient modulus (MPa), q_c is the cone resistance (MPa), f_s is the sleeve friction (MPa), σ_c or σ_3 is the confining stress (kPa), σv is the vertical stress (kPa), w is the water content in decimal number format, γ_d is the dry unit weight (kN/m^3), and γ_w is the unit weight of water (kN/m^3). The coefficients of determination values for both equations are 0.99 and 0.99, respectively.

MRDI 3 (FWD, GeoGauge, and SPA)

The 1993 AASHTO design guide recommends a factor of 0.33 to be multiplied with the FWD backcalculated moduli to determine the design resilient moduli of the subgrades. As described in the earlier sections, this ratio is not unique and varies considerably. This variation was attributed to different soil types, test conditions, and backcalculation programs that provide different moduli predictions. As a result, no quotient factor is recommended here. One should use local experience to determine the resilient moduli. In the case of GeoGauge and SPAs, more research is needed to develop appropriate factors to determine the design resilient moduli.

INDIRECT MODELS

Several other models including those recommended by AASHTO test procedures utilize two-, three-, or four-parameter correlations that account for confining and shearing stresses. Some of these formulations use nondimensional forms of stresses by normalizing confining and deviatoric stresses with atmospheric pressures and others

TABLE 12
SUMMARY OF DCP CORRELATIONS FOR MRDI 1

Reference	Expression	Units
De Beer and van der Marwe (1991)	Log (E_{DCP}) = 3.05 – 1.06 × log (DCP)	DCP in mm per blow
Chai and Roslie (1998)	E in MPa = 2224 × DCP$^{-0.99}$	DCP in blows per 300 mm
Hassan (1996)	M_R in psi = 7013 – 2040.8 ln (DCPI)	DCPI in inches per blow
Chen et al. (1999)	M_R (ksi) = 338 × DPI$^{-0.39}$	DPI in mm per blow
George and Uddin (2006)	M_R in MPa for Sandy Soils = 235.3 × DCPI$^{-0.48}$ M_R in MPa for Clays = 532.1 × DCPI$^{-0.49}$	DCPI in mm per blow
Abu-Farsakh et al. (2004)	ln M_{FWD} = 2.35 + [5.21 /ln PR]	PR in mm per blow
Chen et al. (2007)	M_R (ksi) = 78.05 × DPI$^{-0.67}$	DPI in mm per blow; valid for bases

use direct stress attributes where the model constants are no longer treated as nondimensional entities. Model constants of the correlations consider the nonlinearities in the subgrade moduli properties (Witzack et al. 1995).

The following notation system will be used to identify each of the formulations. MRI2 represents an indirect two-parameter resilient modulus, and MRI3 and MRI4 denote indirect three-parameter and four-parameter resilient modulus formulations. The following sections describe each of these formulations. Because the current practice is to use parameters such as k_1, k_2, k_3, and k_4, the same constant parameters are used for each formulation. In cases in which stresses in the formulations were not normalized, readers should note that these constants and their magnitudes will not be construed as nondimensional. The constants will have units of the stresses that have been used in the modeling analysis.

Two-Parameter Models

MRI2-1

Dunlap (1963) formulated the following model in which the confining stress (σ_3) is used as a stress attribute:

$$M_R = k_1 p_a \left(\frac{\sigma_3}{p_a} \right)^{k_2} \tag{41}$$

where k_1 and k_2 are model constants. This formulation is normalized and hence the model constants are dimensionless. This model formulation does not address the deviatoric stress effects on the test results, which are considered important for better modeling or representation of resilient behavior.

MRI2-2

Seed et al. (1967) formulated the following Equation 42 in which the bulk stress (θ) is used as a stress attribute:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \tag{42}$$

where k_1 and k_2 are model constants, p_a is the atmospheric pressure, σ_3 is the minor principal stress, θ is the bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$, and σ_1 and σ_2 are the major and intermediate principal stresses, respectively. This formulation is normalized and hence the model constants are dimensionless. This model formulation considers deviatoric stress effects on the test results by including their effects in the bulk stress. However, the true influence of deviatoric stress effects is not represented in this formulation. This model is primarily used for granular soils.

MRI2-3

The following power model uses the deviatoric stress (σ_d) as the lone stress attribute in the formulation:

$$M_R = k_1 p_a \left(\frac{\sigma_d}{p_a} \right)^{k_2} \tag{43}$$

where k_1 and k_2 are model constants, p_a is the atmospheric pressure, and σ_d is the deviatoric stress applied during the triaxial test. This formulation is normalized and hence the model constants are dimensionless. This model formulation does not consider confining stress effects on the test results, which is a limitation. This model is primarily used for cohesive soils.

MRI2-4

The following bilinear model for resilient modulus was discussed by Thompson and Elliott (1985). M_R value increases with the deviatoric stress up to a break point beyond which the modulus decreases with an increase in deviatoric stress. The following formulation (Equation 44) is recommended, which uses deviatoric stress (σ_d) as the lone stress attribute:

$$\begin{aligned} M_R &= k_2 + k_3 (k_1 - \sigma_d) \qquad k_1 \rangle \sigma_d \\ M_R &= k_2 + k_4 (\sigma_d - k_1) \qquad k_1 \langle \sigma_d \end{aligned} \tag{44}$$

where k_1, k_2, k_3, and k_4 are model constants, and σ_d is the deviatoric stress applied during the triaxial test. This formulation is not normalized and hence the model constants are dimensional. This model is primarily used for cohesive soils.

MRI2-5

Wolfe and Butalia (2004) developed the following correlation:

$$\frac{M_R}{p_a} = k_1 \left(\frac{p_a \times \sigma_{oct}}{\tau_{oct}^2} \right)^{k_2} \tag{45}$$

where τ_{oct} is octahedral shear stress = $[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{½}/3$; and σ_{oct} is octahedral normal stress = $(\sigma_1 + \sigma_2 + \sigma_3)/3$. This equation is valid for cohesive soils only.

Three-Parameter Models

Several other models were reported in the literature, which use both stresses (either confining and deviatoric stresses or bulk or octahedral stresses) that are functions of confining and deviatoric stresses. Several of these models are presented in the following equations. Again, the same constants are used in each formulation. If a researcher or practitioner uses two of these models in their analysis, it is important to use different constant terms for each model. Otherwise, it would result in confusion to the users.

The most general form of a three-parameter model is as follows (Ooi et al. 2006):

$$M_R = k_1 p_a [f(c)]^{k_2} [g(s)]^{k_3} \tag{46}$$

where $f(c)$ is a function of confinement; $g(s)$ is a function of shear; and k_1, k_2, and k_3 are constants. The effects of confinement in these models can be expressed in terms of the minor principal stress (σ_3), bulk stress (θ), or octahedral stress ($\sigma_{oct} = \theta/3$), while the parameter options for modeling the effects of shear include the deviatoric stress or octahedral shear stress (τ_{oct}). The three-parameter models represented by the Equation 46 are more versatile and apply to all soils (Ooi et al. 2006).

MRI3-1

Uzan (1985) recommended the following formulation:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \tag{47}$$

MRI3-2

Witczak and Uzan (1988) revised Equation 47 by replacing the deviatoric stress with octahedral shear stress:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{\mathrm{p_a}}\right)^{k_3} \tag{48}$$

This formulation is recommended in the 1993 AASHTO design guide.

MRI3-3

Pezo (1993) recommended the following formulation:

$$M_R = k_1 p_a \left(\frac{\sigma_3}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \tag{49}$$

MRI3-4

Ni et al. (2002) recommended the following three-parameter formulation (Equation 50):

$$M_R = k_1 p_a \left(1 + \frac{\sigma_3}{p_a}\right)^{k_2} \left(1 + \frac{\sigma_d}{p_a}\right)^{k_3} \tag{50}$$

where all of the above formulations used the following stresses as their attributes:

τ_{oct} = octahedral shear stress = $[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}/3$;

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$;

σ_d = deviator stress = $\sigma_1 - \sigma_3$;

σ_1, σ_2, σ_3 = major, intermediate, and minor principal stresses, respectively; and

p_a = atmospheric pressure.

The three models (Equations 48, 49, and 50) predict zero resilient modulus when a confining pressure of zero is used in those formulations. Hence, the attributes are revised in Ni et al. (2002), such that they will work for a wide range of stresses.

MRI3-5

Ooi et al. (2004) recommended the following two models with slight modifications to the model developed by Ni et al. (2002):

$$M_R = k_1 p_a \left(1 + \frac{\theta}{p_a}\right)^{k_2} \left(1 + \frac{\sigma_d}{p_a}\right)^{k_3} \tag{51}$$

$$M_R = k_1 p_a \left(1 + \frac{\theta}{p_a}\right)^{k_2} \left(1 + \frac{\tau_{oct}}{p_a}\right)^{k_3} \tag{52}$$

MRI3-6

The NCHRP project 1-28 A and *MEPDG* recommended the following expression for resilient modulus:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(1 + \frac{\tau_{oct}}{p_a}\right)^{k_3} \tag{53}$$

This expression is a simplification of the five-parameter model.

MRI3-7

Gupta et al. (2007) recommended the following expression for resilient modulus for compacted and unsaturated subsoils:

$$M_R = k_1 p_a \left(\frac{\sigma_b - 3k_6}{p_a} \right)^{k_2} \left(k_7 + \frac{\tau_{oct}}{p_a} \right)^{k_3} + \alpha_1 (\mu_a - \mu_w)^{\beta_1} \quad (54)$$

where $(\mu_a - \mu_w)$ is matric suction; k_1, k_2, k_3, k_6, and k_7 are model constants; and α_1 and β_1 are regression constants estimated from clay content or plastic limit. This expression is a simplification of the five-parameter model. The fitting parameters (k_6, and k_7) were reported to be close to 0 and 1 as per the experimental results and analyses reported by Gupta et al. (2007). Further details on this model are reported by Gupta et al. (2007).

The previous equations are valid for both granular and cohesive soil types. Ooi et al. (2004) acknowledged that, although the above equations account for the effects of external stress state on the resilient modulus, they do not account for the internal tensile stress (suction) caused by the soil type, soil structure, and the soil physical state. Overall, however, these equations address and capture both external confinement and shear stress effects on the resilient properties of granular and cohesive soils. Also, as stated by Irwin (n.d.), these nonlinear models can be used in a semi-log format, which can result in better analysis of subgrade stresses including tensile stresses.

CORRELATIONS DEVELOPMENT AND EVALUATION

To address the effects of soil type and test-related variables, several researchers analyzed their test data with the previous model formulations and then determined the model constants. Different forms of regression equations were developed between model constants and soil properties. A summary of these studies is presented in the following sections. Richter (2006) discussed a few of these correlations and their findings with respect to these models. Some of the findings presented here are based on the information provided in Richter (2006). Other factors including the degree of anisotropy and its influence on moduli of aggregates were reported by Tutumleur and Thompson (1997).

Rada and Witczak (1981) provided model constants based on the bulk stress model (Model MR2I-1) for various types of unbound granular materials including aggregates. Table 13 presents the model constants. Richter (2006) observed that a considerable range of model constants for various base materials was reported by Rada and Witczak (1981). The variation was attributed to moisture and density variations as well as material characteristics (Richter 2006).

Santha (1994) presented several model constant correlations based on the resilient moduli data from Georgia. Correlations developed by Santha (1994) as a function of soil properties are presented in Table 14. Validation of the correlations proposed by Santha (1994) showed that these models predicted close to the measured values. Limitations of these correlations include the requirement for several characteristics and possible collinearity problems.

TABLE 13

BULK STRESS BASED MODEL (MODEL 2I-1) CONSTANTS DEVELOPED BY RADA AND WITCZAK (1981) (RICHTER 2006)

Aggregate Class	No. of Data Points	K_1 Parameter (kPa (psi))			K_2 Parameter		
		Mean	SD	Range	Mean	SD	Range
Silty sands	8	11,170 (1620)	5,378 (780)	4,895 to 26,407 (710 to 3830)	0.62	13	0.36 to 0.80
Sand gravel	37	33,646 (4480)	29,647 (4300)	5,929 to 88,529 (860 to 12840)	0.53	17	0.24 to 0.80
Sand-aggregate blends	78	29,992 (4350)	18,133 (2630)	12,962 to 76,325 (1880 to 11070)	0.59	13	0.23 to 0.82
Crushed stone	115	49,711 (7210)	51,642 (7490)	11,756 to 390,726 (1705 to 56670)	0.45	23	−0.16 to 0.86
Limerock	13	27,786 (4030)	70,602 (10240)	39,300 to 578,194 (5700 to 83860)	0.40	11	0.00 to 0.54
Slag	20	167,198 (24250)	137,275 (19910)	64,121 to 636,800 (9300 to 92360)	0.37	13	0.00 to 0.52
All data	271	63,708 (9240)	77,394 (11225)	4,895 to 636,800 (710 to 92360)	0.52	17	−0.16 to 0.86

TABLE 14

CORRELATIONS DEVELOPED FROM MODEL BY SANTHA (1994) (ADAPTED FROM RICHTER 2006)

	Equation	R^2
Granular materials	$LogK_1 = 3.479 - 0.07MC + 0.24\frac{MC}{MOIST} + 3.681COMP + 0.011SLT + 0.006CLY - 0.025SW - 0.039DEN + 0.004(\frac{SW^2}{CLY}) + 0.003(\frac{DEN^2}{S}40)$	0.94
	$K_2 = 6.044 - 0.053MOIST - 2.076COMP + 0.0053SATU - 0.0056CLY + 0.0088SW - 0.0069SH - 0.027DEN + 0.012CBR + 0.003^{SW^2/CLY} - 0.31(SW+SH)/CLY$	0.96
	$K_3 = 3.752 - 0.068MC + 0.309MCR - 0.006SLT + 0.0053CLY + 0.026SH - 0.33DEN - 0.0009(SW^2/CLY) + 0.00004(SATU^2/SH) - 0.0026(CBR*SH)$	0.87
Fine-grained materials	$LogK_1 = 19.813 - 0.045MOIST - 0.131MC - 9.171COMP + 0.037SLT + 0.015LL - 0.016PI - 0.021SW - 0.052DEN + 0.00001(S40*SATU)$	.95
	$K_3 = 10.274 - 0.097MOIST - 1.06MCR - 3.471COMP + 0.0088S40 - 0.0087PI + 0.014SH - 0.046DEN$	0.88

Note: MC = moisture content; MOIST = optimum moisture content; SATU = percent saturation; COMP = percent compaction; S40 and S60 = percents passing numbers 40 and 60 sieves; CLY = percent clay (CLY); SLT = percent silt (SLT); SW = percent swell (SW); SH = percent shrinkage; DEN = density; and CBR = California Bearing Ratio.

Another study conducted by Titus-Glover and Fernando (1995) presented model constants derived using MR3I-1 on various materials. Table 15 presents these constants and results. Richter (2006) noted that these results ranged considerably based on different material types. Maher et al. (2000) also reported several model constant parameters based on MR3I-1 on various New Jersey subgrades. Table 16 presents these results.

TABLE 15

MODEL CONSTANTS FROM TITUS-GLOVER AND FERNANDO 1995 STUDY (RICHTER 2006)

Material	K_1	K_2	K_3
Limestone	243	0.95	$-6.5*10^{-5}$
Iron ore	75	1.01	$-2.2*10^{-3}$
Sandy gravel	152	0.88	$-2.9*10^{-4}$
Caliche	322	0.88	$-9.8*10^{-5}$
Shellbase	318	0.80	$-9.8*10^{-5}$
Sand	498	0.77	−0.01
Silt	195	0.071	$-6.5*10^{-5}$
Lean clay	195	0.068	−0.19
Fat clay	122	0.19	−0.36

Wolfe and Butalia (2004) attempted a comprehensive evaluation of various models, including both direct and indirect models, to predict various resilient moduli properties. Figure 83 presents comparisons of various model predictions of resilient properties with measured moduli. The models termed in the figure correspond to the U.S. Department of Agriculture model, Hyperbolic model (MRDS 7), Georgia DOT model (Table 14), TxDOT model (MRDS 11), [spell out]UCS model (MRDS 4), and Ohio model (MRDS 4).

From Figure 83, it can be mentioned that the M_R predicted from the six models shows large variations with the laboratory results for all the soil samples. Wolfe and Butalia (2004) noted that the existing models are not capable of providing accurate predictions of moduli. Variations in the model predictions and measured moduli can be attributed to differences in soil types and test procedures. The resilient

TABLE 16

MODEL CONSTANTS FOR NJ SUBGRADES FROM MAHER ET AL. (2000)

Soil Location	AASHTO Classification	Moisture Content Type	Soil Parameter (k_1)	Soil Parameter (k_2)	Soil Parameter (k_3)	Coefficient of Determination (r^2)
Rt. 23	A-1-b	2% Wet	521.62	0.93	-0.2068	0.99
		OMC	834.48	0.6803	-0.0792	0.95
		2% Dry	1032.07	0.7713	-0.2774	0.94
Rt. 46	A-2-4	2% Wet	314.54	0.7532	-0.4614	0.94
		OMC	410.71	0.7026	-0.4046	0.91
		2% Dry	410.56	0.8072	-0.4166	0.96
Rt. 80a	A-2-4	2% Wet	340.97	0.7675	-0.4948	0.96
		OMC	440.57	0.5085	-0.3913	0.89
		2% Dry	599.39	0.6571	-0.2769	0.91
Rt. 295	A-3	2% Wet	344.81	0.6029	-0.3921	0.91
		OMC	399.77	0.7107	-0.3973	0.93
		2% Dry	413.94	0.5674	-0.3986	0.96
Rt. 80b	A-4	2% Wet	346.48	0.7448	-0.5927	0.97
		OMC	433.4	0.6982	-0.3497	0.91
		2% Dry	585.62	0.7453	-0.275	0.97
Rt. 206	A-4	2% Wet	273.71	0.6025	-0.5177	0.92
		OMC	389.67	0.6515	-0.4161	0.94
		2% Dry	539.87	0.7211	-0.3934	0.93
Cumberland County	A-6	2% Wet	202.6	0.4735	-0.8388	0.95
		OMC	1278.9	0.2636	-0.2343	0.94
		2% Dry	1699.32	0.231	-0.1707	0.92
Cumberland County	A-7	2% Wet	284.32	0.3307	-0.7753	0.89
		OMC	1290.4	0.2262	-0.1864	0.89
		2% Dry	1430.67	0.2748	-0.1173	0.88

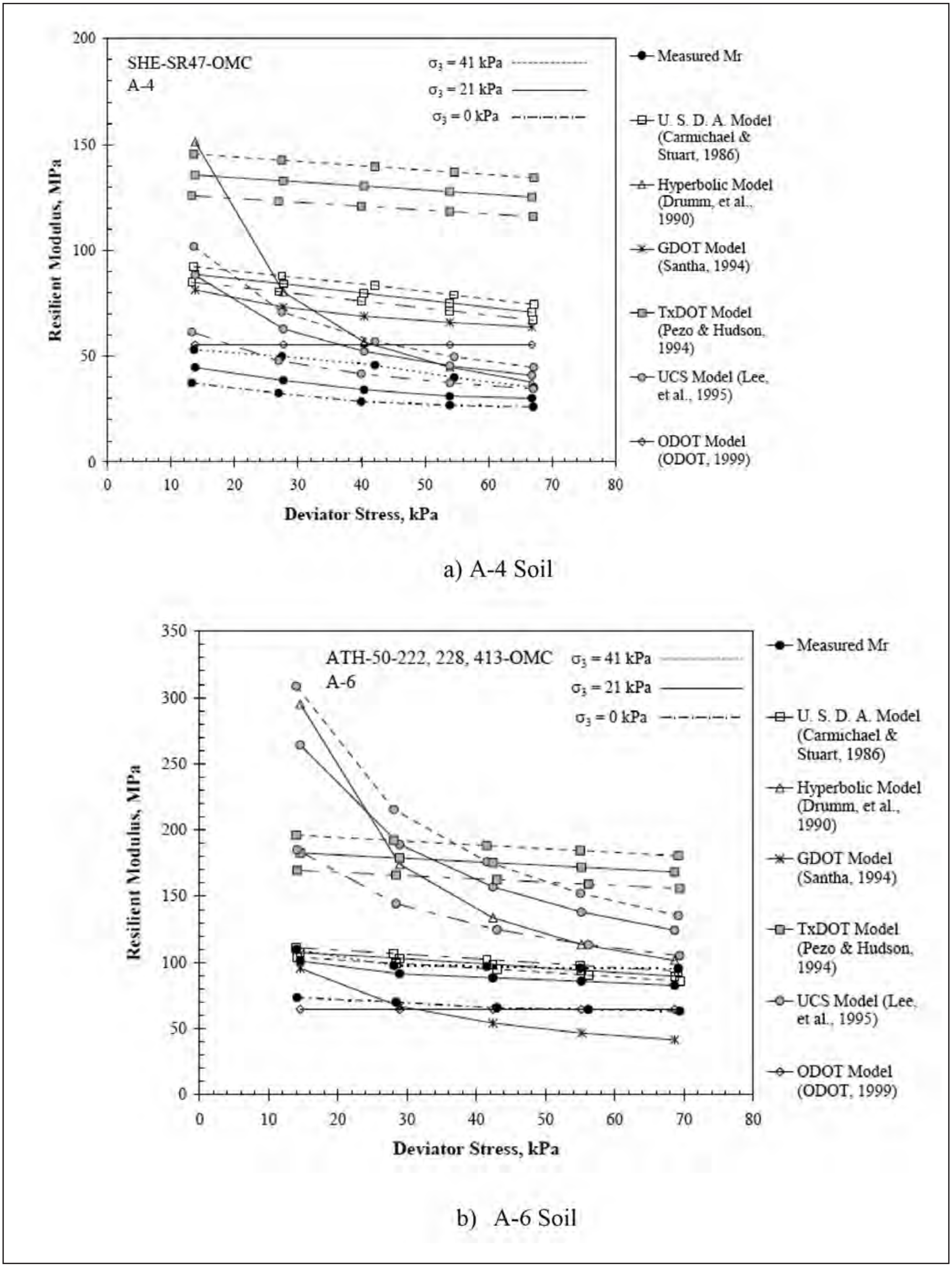


FIGURE 83 Comparisons of various model predictions and measured moduli (Wolfe and Butalia 2004).

moduli were measured using the AASHTO T294-94 procedure, whereas the predicted moduli were based on earlier AASHTO procedure data. This eventually resulted in the development of a new Model 2I-5. This model has two constant parameters. Researchers analyzed their resilient moduli data with this model and provided the following model constant equations as a function of soil properties (see Figure 84). Backcalculation of the moduli and their comparisons for select soils are also presented in Figure 85, which indicates an excellent match with the measured moduli.

Malla and Joshi (2006) used the MR3I-2 formulation and analyzed several subgrades from New England states. Various constant parameters derived from this study were then correlated with soil properties and compaction variables. Table 17 provides various model constant parameters developed for coarse-grained soils, coarse-grained soils with CU ≤ 100, and fine-grained soils.

Prediction of resilient moduli using these relationships was made with the measured moduli in the same tables. The coefficients of determination for most of these relationships are close to 0.40, indicating that these correlations could be considered as average at best. Malla and Joshi (2006) also developed individual soil correlations (AASHTO soil type) based on the measured test data. These correlations have higher R^2 values, suggesting that these correlations are better than those developed for the grouped soil correlations of Table 17.

Titi et al. (2006) used the MR3I-6 correlation, which was recommended by the *MEPDG* guide. This study determined the model constant parameters for different Wisconsin subgrades and these constant parameters are then correlated with various basic soil properties. A total of 136 test results were analyzed in the determination of model constant parameters, k_1, k_2, and k_3.

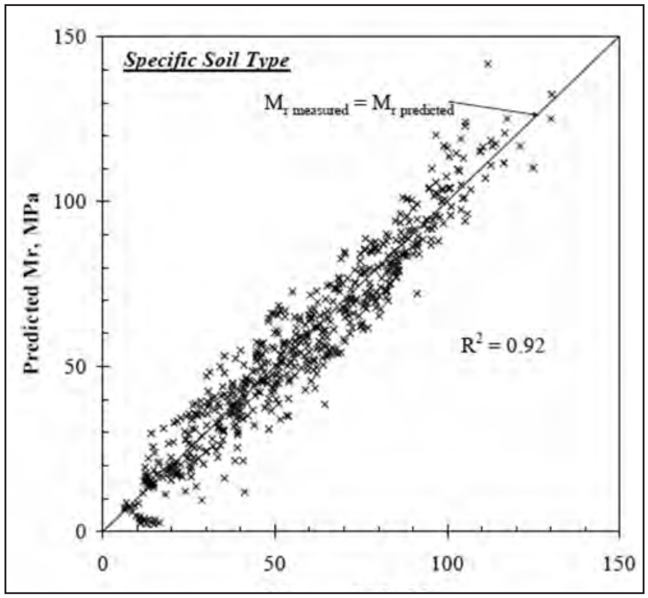


FIGURE 85 Comparisons between model predictions and measured resilient moduli (Wolfe and Butalia 2004).

$$k_1 = a_1 \sigma_3^{\ a_2} + a_3 \left(\frac{S}{100} \right)^{a_4} + a_5 q_u + a_6 PI + a_7 (LL - w) + a_8 (w_{opt} - w)$$
$$+ a_9 (\%passing\ \#200 - a_{10})$$

$$k_2 = b_1 \sigma_3^{\ b_2} + b_3 \left(\frac{S}{100} \right)^{b_4} + b_5 q_u^{\ b_6} + b_7 PI + b_8 LL$$

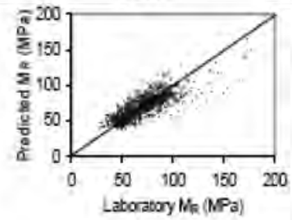
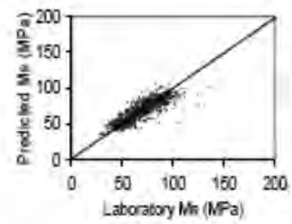
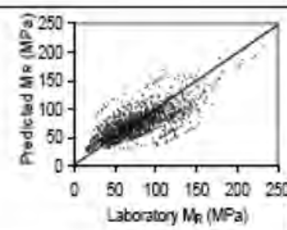
where: $a_1 = a_{11} + a_{12} \left(\frac{w_{opt} - w}{w_{opt}} \right)$

$b_1 = b_{11} + b_{12} \left(w - w_{opt} \right)$

w_{opt}	= Optimum Moisture Content (%)
w	= Sample Moisture Content (%)
σ_3	= Confining Stress (kPa)
S	= Degree of Saturation (%)
q_u	= Unconfined Compressive Strength (kPa)
PI	= Plasticity Index
LL	= Liquid limit
%passing #200	= percent soil particles finer than 0.075mm

FIGURE 84 Model 2I-5 constant equations recommended by Wolfe and Butalia (2004).

TABLE 17
MODEL CORRELATIONS DEVELOPED BY MALLA AND JOSHI (2006)

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

Several independent variables are used to reflect soil type and current soil physical condition (Titi et al. 2006). These are percent passing sieve #4 ($P_{No.4}$), percent passing sieve #40 ($P_{No.40}$), percent passing sieve #200 ($P_{No.200}$), liquid limit (LL), plastic limit (PL), plasticity index (PI), liquidity index (LI), amount of sand (%Sand), amount of silt (%Silt), amount of clay (%Clay), water content (w), and dry unit weight (γ_d). The optimum water content (w_{opt}.) and maximum dry unit weight (γ_{dmax}) and combinations of variables were also included (Titi et al. 2006). The developed models were evaluated based on the multiple collinearity problems and coefficient determination values.

Table 18 presents equations recommended for fine-grained, plastic coarse-grained, and nonplastic coarse-grained soils. Figure 86 presents a typical comparison analysis for fine-grained soils. The results show that the predicted moduli using recommended equations matched well with measured moduli.

Titi et al. (2006) also presented a comprehensive analysis in which they predicted moduli using correlations developed from the LTPP database by Yau and Von Quintus (2004) and compared the correlations with the measured moduli of their study. They noted considerable differences between predictions and measurements, which were attributed to differences in test procedures and other conditions present in the LTPP database.

MATRIX TABLES

In this section, the existing literature information is summarized in a matrix format. The main focus of the table is to provide a thorough assessment of various laboratory and field methods for determining the resilient properties of unbound bases and subgrades. Again, this assessment is based on the available information presented in this report.

Tables 19 and 20 provide a matrix-style comparison of various items, including applicable soil types, relation to design modulus, type of M_R interpretation (direct or indirect), standardization, need for skilled personnel to perform the test, cost details, applicability in new pavement construction projects, pavement rehabilitation projects, need of additional tests for validation, and type of M_R correlations that the test results provide. Table 21 presents an overview of the assessments of the modeling correlations. Assessments are based on repeatability and reliability of correlations,

TABLE 18
CORRELATIONS DEVELOPED FOR WISCONSIN SUBGRADE SOILS (TITI ET AL. 2006)

Soil type	Model Correlations
Fine-Grained Soils	$k_1 = 404.166 + 42.933PI + 52.260\gamma_d - 987.353\left(\frac{w}{w_{opt}}\right)$ $k_2 = 0.25113 - 0.0292PI + 0.5573\left(\frac{w}{w_{opt}}\right)\times\left(\frac{\gamma_d}{\gamma_{d\max}}\right)$ $k_3 = -0.20772 + 0.23088PI + 0.00367\gamma_d - 5.4238\left(\frac{w}{w_{opt}}\right)$
Coarse-grained, non-plastic	$k_1 = 809.547 + 10.568P_{No.4} - 6.112P_{No.40} - 578.337\left(\frac{w}{w_{opt}}\right)\times\left(\frac{\gamma_d}{\gamma_{d\max}}\right)$ $k_2 = 0.5661 + 0.006711P_{No.40} - 0.02423P_{No.200} + 0.05849(w - w_{opt})$ $+ 0.001242(w_{opt})\times(\gamma_{d\max})$ $k_3 = -0.5079 - 0.041411P_{No.40} + 0.14820P_{No.200} - 0.1726(w - w_{opt})$ $- 0.01214(w_{opt})\times(\gamma_{d\max})$
Coarse-grained, Plastic	$k_1 = 8642.873 + 132.643P_{No.200} - 428.067(\%Silt) - 254.685PI + 197.230\gamma_d$ $- 381.400\left(\frac{w}{w_{opt}}\right)$ $k_2 = 2.3250 - 0.00853P_{No.200} + 0.02579LL - 0.06224PI - 1.73380\left(\frac{\gamma_d}{\gamma_{d\max}}\right)$ $+ 0.20911\left(\frac{w}{w_{opt}}\right)$ $k_3 = -32.5449 + 0.7691P_{No.200} - 1.1370(\%Silt) + 31.5542\left(\frac{\gamma_d}{\gamma_{d\max}}\right) - 0.4128(w - w_{opt})$

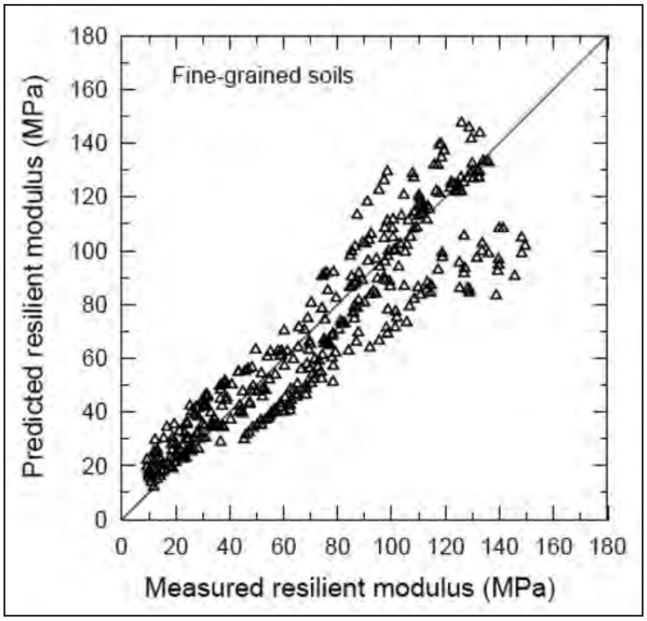


FIGURE 86 Comparisons between measured and predicted moduli of fine grained soils (Titi et al. 2006).

need for additional laboratory-based studies for validation, requirements of stress analysis, and other factors.

Most of the assessments noted in these tables are based on the technical information available to the author, and because it is subjective, these assessments should be considered as suggestive assessments.

RESILIENT MODULI MAGNITUDES

A summary of moduli of various bases and subgrade materials is presented in this section. The moduli ranges from study to study are different, and these variations are attributed to material and sampling differences as well as to test procedure and equipment variations. Because it is not practical to summarize this information in this synthesis, some of the moduli information from a few studies (including one from an LTPP study) is presented in Appendix D.

The recommended approach to determine the resilient moduli of soils is to test and measure the moduli of subgrade

TABLE 19

COMPREHENSIVE ASSESSMENTS OF VARIOUS METHODS FOR DETERMINING RESILIENT PROPERTIES—PART I

	Subgrades							
Method	Clayey	Sandy	Unbound Bases	Relationship with Design M_R (nature of correlations)	Is this Method Standardized?	Skillled Personnel Required?	Time to Perform (quick/long)	Cost (relative)
Lab—RLT	Y	Y	Y	Y (direct, Level 1)	Y	Y	Long	High
Lab—Resonant Column	Y	Y	Y	N (indirect, needs Poisson's ratio)	Y	Y	Long	Moderate
Lab—Others (CBR, R)	Y	Y	Y	N, indirect (Level 2)	Y	N	Quick	Low to Moderate
Field—FWD	Y	Y	Y	N, direct (Level 1/2)	N	Y	Quick	Low to Moderate
Field—Geogauge	Y	Y	Y	N, indirect (Level 2)	N	N	Quick	Low to Moderate
Field—PSA	Y	Y	Y	N, indirect (Level 2)	N	N	Quick	Low to Moderate
Field—LFWD	Y	Y	Y	N, direct (Level 1/2)	N	N	Quick	Low
Field—DCP	Y	Y	N	N, indirect (Level 2)	Y	N	Quick	Low
Field—CPT	Y	Y	N	N, indirect; R	N	Y	Quick	Moderate to High

Note: Y = yes; N = no; R = needs more research.

TABLE 20

COMPREHENSIVE ASSESSMENTS OF M_R PREDICTION MODELS

Model Type	Applicable: Subgrade	Applicable: Unbound Bases	Repeatability	Reliability	Needs Additional Laboratory Studies for Verification?	Stress Estimation in the Bases and Subgrades	Need More Data and Research?
Direct Correlations Based on Laboratory Determined Parameters	Y	Y	Y	Moderately Reliable	Y	Not Needed	Y
Direct Correlations Based on Field Determined Parameters	Y	Y	Y	Moderately Reliable	Y	Not Needed	Y, R
Indirect Correlation Parameters—2 Model Constants	Y	Y	Y	Low to Moderately Reliable	Y	Needed	Y
Indirect Correlation Parameters—3 Model Constants	Y	Y	Y	Moderately to Highly Reliable	Y	Needed	Y, R

Note: Y = yes; N = no; R = needs more research.

TABLE 21

COMPREHENSIVE ASSESSMENT OF VARIOUS METHODS FOR DETERMINING RESILIENT PROPERTIES—PART II

Method	Sampling Needed?	Applicable in New Pavement Construction?	Applicable in Pavement Rehabilitation?	Applicable in QC/QA for Base/Subgrade Compaction?	Non-Destructive Nature of Testing?	Correlations Type?	Needs Additional Lab Studies for Verification?
Lab—RLT	Y	Y	Y	N	Y	Semi-empirical	N
Lab—Resonant Column	Y	Y	Y	N	Y	NA	N
Lab—Others (CBR, R)	Y	Y	Y	N	N	Empirical	Y
Field—FWD	N	Y	Y	Y	Y	Theoretical (back-calculated)	Y (validation of backcalculated moduli)
Field—Geogauge	N	Y	Y	Y	Y	Theoretical (back-calculated)	Y (validation of interpreted moduli)
Field—PSA	N	Y	Y	Y	Y	Theoretical (back-calculated)	Y (validation of interpreted moduli)
Field—LFWD	N	Y	Y	Y	Y	Theoretical (back-calculated)	Y (validation of interpreted moduli)
Field—DCP	N	Y	Y	Y	N	Empirical	Y (validation of interpreted moduli)
Field—CPT	N	Y	Y	Y	N	Semi-empirical to empirical	Y (validation of interpreted moduli)

Note: Y = yes; N = no; NA = not applicable; R = needs more research.

and base materials. In cases in which testing equipment are not available, a threshold value based on the available soil property range in the literature or a value determined from M_R empirical correlations is chosen. In such cases, engineering judgment should be exercised. Recommended approaches for determining resilient or elastic moduli are mentioned in chapter six.

SUMMARY

It is difficult to list the modeling component of each resilient modulus study performed in the literature. In most of these studies, the correlations developed are shown to predict the moduli properties accurately, as observed by two studies reported here by Santha (1994) and Maher et al. (2000). Problems arise when the correlations developed elsewhere are tested on different soils. As shown by Wolfe and Butalia (20004) and Malla and Joshi (2006), the model correlations provide poor predictions when used on other soils. Such problems should be expected because correlations are developed from data that may have shown large variations for similar types, similar compaction, and stress conditions.

For example, Von Quintus and Killingsworth (1998) and Yau and Von Quintus (2002, 2004) developed correlations from the LTPP database that showed high R^2 values from the statistical regression analysis. When attempted on other soils for other states, however, these correlations have provided poor predictions of resilient properties. This reveals that newer routine analyses are needed or that the test database needs to be carefully screened before it is used to develop correlations. Screening of the data is needed to address the material variability, quality controls in testing, and variability of testing methods used to determine resilient properties.

Recent exercises using more rigorous statistical approaches by following “joint estimation and mixed effects” appear to provide good correlations (Archilla et al. 2007). Archilla et al. (2007) mentioned one such procedure in the recent yet unpublished[still in press or published in 2007?] research. Independent validation studies are needed to evaluate and better understand these methods in providing improved resilient moduli predictions.

Other methods such as the one developed by Han et al. (2006) use statistical approaches in an expert system for predicting resilient properties. In this method, the user is given four alternate methods, one based on certainty rules and three based on statistical methods, to predict resilient properties. Based on the reasonableness and accuracy of the data provided by the user, the expert system picks the model and provides predictions of moduli. Han et al. (2006) noted that, although the initial validation studies show encouraging results, more research studies are needed to improve the quality of the estimation. These recent studies all show that the new analyses are providing directions that could lead to better estimation of resilient properties of both bases and subgrades using powerful statistically intensive tools.

CHAPTER SIX

USEFUL PRACTICES, CONCLUSIONS, AND FUTURE RESEARCH NEEDS

USEFUL PRACTICES FOR DETERMINING RESILIENT PROPERTIES

One of the objectives of this synthesis is to list various practices for determining the resilient properties of materials. Of these, certain practices are identified as particularly useful for laboratory methods, field nondestructive and intrusive testing, and modeling correlations to determine resilient properties. Identification of these methods is based on the comprehensive literature review as well as the survey responses from various departments of transportation (DOTs). These methods should not be construed as endorsements by this synthesis study. Instead, the state DOTs are strongly urged to develop their own practices by considering those recommended here and then evaluating them to determine the realistic resilient moduli or stiffness results of their local soils.

Laboratory Methods (Level 1 Parameters)

Among the laboratory tests, a useful method is to perform a standardized test method utilizing the repeated load triaxial (RLT) equipment. AASHTO test procedure T-307 can be employed to perform Resilient Modulus (M_R) tests on both subgrades and unbound bases under laboratory conditions. For unbound bases, procedures developed for granular materials in the T-307 method can be used.

At least three tests might be conducted on identical soil specimens for each type of soil encountered at the project site, and the average moduli results from these three tests can be used for the pavement design. For subgrade specimen preparation, an impact compaction method may be used. For base specimens, a similar method or vibratory compaction is recommended. To reduce system compliance errors, in particular when testing stiffer and base materials, end grouting may be used for the soil specimens. Both internal and external displacement monitoring systems may be used. Although the former method provides slightly higher moduli, the practical problems of installation and slipping during testing necessitate the use of external linear variable differential transformers (LVDTs) for displacement monitoring.

Other laboratory testing methods, including California Bearing Ratio value, R value, and Soil Support Value, and other soil properties, are used to determine M_R by means of indirect correlations. Such practice will lead to the use of Level 2 and Level 3 types of M_R design inputs for *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*). Seismic laboratory methods using bender element or resonant column tests are also successfully used by certain agencies to determine soil moduli for pavement design and other applications. Such practices are best left to those agencies for their consideration.

Field Methods—Nondestructive (Level 1 Parameters)

Falling Weight Deflectometer (FWD), a field nondestructive test, is useful as a field method for determining moduli of both subgrades and bases. This approach has been used by several DOTs with reasonable success, as observed from the survey results presented in chapter two. Different backcalculation software is successfully used by DOTs to analyze FWD data to determine the backcalculated moduli. Hence, no single software is singled out for FWD backcalculation analysis.

Also, several portable Light Falling Weight Deflectometers (LWDs) are used for both estimation of moduli and determination of compaction quality of subgrades and bases. More research on these LWD methods will provide better evaluation of their potential to interpret field moduli, which may lead to future implementation of this method for pavement design.

Field Methods—Intrusive (Level 1 Parameters)

The dynamic cone penetration (DCP) method is a useful tool for in situ evaluation of stiffness and also to address compaction quality of subgrades. Several local correlations are developed and used by various DOTs for determining the stiffness properties of local soils, and hence there is no single best practice or correlation type for determining moduli of local soils. Though other in situ test methods have been used for M_R studies, their usage and application potentials are yet to be addressed in a comprehensive manner.

Correlations—Direct and Indirect (Level 2 Parameters)

Although a large number of correlations currently exist, their accuracy is still unknown to pavement designers. Independent assessments or validation studies with the local soil database may be conducted before using them. Overall, the following methods have been found useful, both as a result of high coefficient determination values or the potential to capture the nonlinear resilient behavior of subgrades and bases:

- Direct Models for Subgrades and Unbound Bases: MRDS 3, MRDS 4, and MRDS 6 (Laboratory-Based Correlations) (MR stands for Resilient Modulus and DS stands for Direct Correlations and Soil Properties–Based Relationship); and MRDI-1 (Field Method Correlation) (MR stands for Resilient Modulus and DI stands for Direct and In Situ Test–Based Relationship).
- Indirect Models for Subgrades and Unbound Bases: MRI2-5 (two-parameter model); and MRI3-3, MRI3-4, and MRI3-5 (three-parameter models).

USEFUL APPROACHES TO PAVEMENT DESIGN

For new pavement design projects and overlay design, the moduli of unbound bases and subgrade are needed. In such designs, Level 1 input parameters are needed, which can be determined by performing laboratory-recommended RLT tests on the quality core specimens retrieved from field sites. The AASHTO T-307 method is useful for determining moduli values at various combinations of stresses for both unbound granular and subgrades. The design moduli values can be established from the measured moduli based on the confining and deviatoric stresses that are representative of the base and subgrade locations in the pavement systems. If several soils exist at a project site, the preferred practice is to determine the moduli for each soil type. If such practice is not practical, engineers can select a weak soil type along the pavement project site and then test that soil for design moduli. This may result in uneconomical yet safe pavement design sections.

Level 1 moduli parameters of bases and subgrades can also be established from field studies using nondestructive FWD studies or intrusive DCP methods. Field test methods discussed in chapter four are useful here. Level 2 design parameters can be determined based on correlations between stiffness properties and soil conditions. A few correlation types are given in chapter five. Validation of the correlations with local soil database including stiffness properties is highly recommended before using them to determine the stiffness values. Level 3 design parameters use assumed soil properties for pavement design and such practice may not be useful except in cases in which such soil parameters are approved by the local geotechnical/material engineers in the department.

CONCLUSION

This synthesis covers various resilient moduli tests and field procedures through direct and indirect methods for either measuring or interpreting the resilient properties of unbound pavement base materials and subgrades. In laboratory test measurements, laboratory direct test methods and laboratory indirect test methods using geophysical measurements are covered.

In field methods, nondestructive tests, such as FWD, GeoGauge, seismic pavement analyzer (SPA), and LWD methods, as well as in situ intrusive tests, such as DCP and cone penetration tests, are summarized and discussed. In each method, both advantages and disadvantages are mentioned. This section is followed by a comprehensive summary of direct and indirect correlations for the determination of resilient modulus properties of subgrades and unbound bases.

Following are some of the major findings from the present synthesis:

- The use of M_R properties of bases and subgrades in pavement design has been increasing among transportation agencies, with some preferring to use direct testing utilizing triaxial equipment, others using field devices, and the rest using correlations to predict moduli. However, there remains a certain amount of skepticism among the engineers and practitioners, which could be attributed to the constant modifications to the resilient moduli test procedures, development of new equipment and devices for laboratory and field measurements of moduli, and confusion caused by various definitions of moduli measured at different strain levels. Other factors include poor reproducibility of test results and backcalculations and lack of standardized procedures. Through the use of surveys and literature reviews, it is clear that certain state agencies prefer using modified standard test procedures, new equipment, or both to measure moduli parameters for the pavement design practice. States such as Minnesota, Louisiana, and Texas belong to this category. Such practices should be encouraged because these states address the appropriate use of measured modulus as a design modulus for flexible pavement design.
- Certain survey respondents expressed concerns with respect to long correlations and complicated triaxial test methods. Oversimplification will ruin the whole design practice; however, the use of empiricism to a certain level to simplify the current correlations will help several DOT agencies better implement the moduli in design practices.
- The synthesis identified different laboratory methods and nondestructive methods as well as field intrusive and in situ LWD methods for determining soil moduli. Among them, the RLT test is the most preferred form of laboratory test for repeatable and reliable moduli property determination. In the field, nondestructive tools such as FWD and an intrusive method such as DCP are preferred field test methods. The latter was also used

to address compaction quality control. The majority of the correlations with DCP are local and empirical types. Reasons for these are a lack of standardization (this method was recently standardized by ASTM and currently there is no standardized AASHTO test procedure) and different modes of devices being used in various states. As a result, measured data from various materials are different, and hence the use of local correlations or the need for additional tests for verification should be reviewed and considered.

- FWD studies are being used with varying levels of success in the present field studies. This was evident from the state surveys, as nearly 60% of the survey respondents (equivalent to 50% of the total DOTs in the United States) noted that they use FWD for different applications, including new pavement construction and pavement rehabilitation projects. Still, there appears to be some variation with respect to the back-calculation programs used for determining moduli of layers. Three programs—MODULUS, EVERCALC, and ELMOD—are being used or mentioned as a preferred program by more than one DOT in their survey responses.
- Other nondestructive methods such as GeoGauge and SPA have been used successfully to determine the composite moduli and soil moduli (in the case of DSPA). As long as the soil moduli determined by these devices are defined properly with respect to design resilient moduli, the use of these devices should be encouraged within the DOTs.
- LWDs have become powerful tools for quick assessments of moduli in the field. However, only a few DOTs are using them or addressing them in a research study environment. More studies will lead to potential implementation of these devices in both determining the moduli of compacted subgrades and bases and assessing the compaction quality conditions. These devices may offer an alternate to nuclear-based gauges that are currently used in the practice for determining the relative compaction of the compacted materials.
- From the studies and surveys, the nonlinear nature of resilient moduli appears to be well accepted by the DOTs as the majority of them have been using various three-parameter models that account for confining and deviatoric stresses of the subgrades and bases. One of the concerns from this synthesis is the availability of several three-parameter models that have been used in the practice. These models along with the current three-parameter model recommended by *MEPDG* create a considerable dilemma for the users when choosing an appropriate correlation to analyze the moduli data.
- From both surveys and modeling results of chapters two and five, it is apparent that the development of universal resilient moduli will be a difficult task with the current stiffness database because of a high level of scatter in the test data. Local correlations are essential; however, it is time to separate the current database of soil and base layer properties that are obtained using the AASHTO T-307 test method from other test laboratory test methods and field methods. This separated database should be used to develop better statistical and intelligent formulations to predict moduli. A few such formulations are discussed in the chapter five summary.

FUTURE RESEARCH NEEDS

One of the problems learned from the Geotechnical/Materials group survey is the fatigue in a small group of geotechnical/materials users with respect to resilient modulus testing and implementation of this method in the flexible pavement design. One respondent noted during telephone communication (in the follow-up surveys) that the test methods are being constantly revised, which leaves users confused. Several others are not interested in exploring both laboratory and field methods for moduli determination, because they mostly rely on indirect correlations using group index parameters, or *R* or California Bearing Ratio values. All these point to the need for better training modules to explain the importance of resilient moduli or stiffness of the materials in a mechanistic pavement design approach.

To achieve these goals, it is important to develop a series of action items, including a few research needs, to promote the use of moduli of unbound bases and subgrades in the flexible pavement design. These action items include the following:

- Explain the importance of Level 1 input parameters for better pavement design.
- Encourage the use of Level 2 moduli input from correlations assuming the correlations are statistically superior and provide reasonable moduli values.
- Standardize test procedures, both in laboratory (current method of T-307 vs. Harmonized method) and field conditions (<u>Research Need</u>).
- Promote acceptance of field nondestructive studies and intrusive studies with standardized protocols (<u>Research Need</u>).
- Address seasonal moisture variations and their effects on moduli of soils and unbound bases along the lines suggested by the *MEPDG* (<u>Research Need</u>).
- Define design moduli and their correlations with various moduli determined from other field devices and methods (<u>Research Need</u>).
- Emphasize the cost-effectiveness (life-cycle cost-benefit studies) and non-nuclear-based methods for quality control of compaction of subgrades and bases (<u>Research Need</u>).
- Develop training modules that emphasize the test methods cited earlier and how they can be used for a realistic pavement design using *MEPDG* (<u>Research Need</u>).

Simplification of test procedures and design methods needs to be considered, but it should not be the sole high priority owing to the complex nature of a performance-based mechanistic pavement design method using moduli properties. A Transportation Pooled Fund program initiated a research study in 2007, which is aimed at improving the resilient modulus test procedures for unbound materials. The goals of this 5-year pooled fund study are (1) to reduce the variability associated with resilient modulus testing of unbound materials, (2) to conduct a precision and bias study of the test procedure, and (3) to provide assistance to states to properly equip and set up a laboratory for successful M_R testing. Similar studies are needed to address the use of nondestructive studies for moduli interpretations of subgrades and unbound bases and compaction quality assessments.

The majority of the synthesis information show considerable advances made by several DOTs in the flexible pavement design area using moduli of subgrades and unbound bases. Focusing on these positives along with a universal implementation of a standardized M_R measurement approach in both laboratory and field conditions will lead to a better and reliable moduli database. Such a database should be used to derive universal statistical correlation models for better interpretation of moduli properties of bases and subgrades.

REFERENCES

Abu-Farsakh, M., K. Alshibli, M. Nazzal, and E. Seyman, *Assessment of In Situ Test Technology for Construction Control of Base Course and Embankments*, Final Report No. FHWA/LA.04/385, Louisiana Transportation Research Center, Baton Rouge, May 2004.

Alaska Pavement Design Manual, DOT&PF Research Report FHWA-AK-RD-03-01, Alaska Department of Transportation and Public Facilities, Juneau, Apr. 2004.

Alavi, S., T. Merport, T. Wilson, J. Groeger, and A. Lopez, *LTPP Materials Characterization Program: Resilient Modulus of Unbound Materials* (*LTPP Protocol P46*) *Laboratory Startup and Quality Control Procedure*, Report No. FHWA-RD-96-176, Federal Highway Administration, McLean, Va., 1997.

Allen, J. and M.R. Thompson, "Resilient Response of Granular Materials Subjected to Time Dependent Lateral Stresses," *Transportation Research Record 510*, Transportation Research Board, National Research Council, Washington, D.C., 1974, pp. 1–13.

American Association of State Highway and Transportation Officials, *Interim Design Guide for Design of Pavement Structures,* Washington, D.C., 1986.

American Association of State Highway and Transportation Officials, *Interim Method of Test for Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials*, T 292-91l, Washington, D.C., 1991.

American Association of State Highway and Transportation Officials, *Guide for Design of Pavement Structures*, Washington, D.C., 1993.

Amini, F., *Potential Applications of Dynamic and Static Cone Penetrometers in MDOT Pavement Design and Construction*, Final Report for Mississippi Department of Transportation, Jackson State University, Jackson, Miss., 2003.

Andrew, J.W., N.M. Jackson, and E.C. Drumm, "Measurement of Seasonal Variations in Subgrade Properties," *Proc., Application of Geotechnical Principles in Pavement Engineering*, ASCE Special Publication, No. 85, 1998, pp. 13–38.

Archilla, A.R., P.S.K. Ooi, and K.G. Sandefur, "Estimation of a Resilient Modulus Model for Cohesive Soils Using Joint Estimation and Mixed Effects," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 133, No. 8, 2007, pp. 984–994.

Asphalt Institute, *Research and Development of the Asphalt Institute's Thickness Design Manual*, 9th ed., Manual Series No. 1, The Asphalt Institute, College Park, Md., 1982.

Barksdale, R.D., "Compressive Stress Pulse Times in Flexible Pavements for Use in Dynamic Testing," *Highway Research Record 345*, Highway Research Board, Washington, D.C., 1971, pp. 32–44.

Barksdale, R.D., "Laboratory Evaluation of Rutting in Base Course Materials," *Proc., 3rd International Conference on Asphalt Pavements*, University of Michigan, Ann Arbor, 1972, pp. 161–174.

Barksdale, R.D., J. Alba, P.N. Khosla, R. Kim, P.C. Lambe, and M.S. Rahman, "Laboratory Determination of Resilient Modulus for Flexible Pavement Design," *NCHRP Web Document 14*, Federal Highway Administration, Washington, D.C., 1997, 486 pp.

Baus, R.L. and T. Li, *Investigation of Graded Aggregate Bases*, FHWA/SCDOT Report No. FHWA-SC-06-03, University of South Carolina, Columbia, Feb. 2006.

Bayomy, F. and H. Salem, *Monitoring and Modeling Subgrade Soil Moisture for Pavement Design and Rehabilitation in Idaho: Phase III: Data Collection and Analysis*, Final Report, National Institute for Advanced Transportation Technology, University of Idaho, Moscow, 2004/2005.

Bennett, T. and M.H. Maher, *The Development of a Performance Specification for Granular Base and Subbase Material*, FHWA NJ 2005-03, Rutgers University, Piscataway, N.J., Feb. 2005.

Berg, R.L., S.R. Bigi, J.A. Stark, and G.D. Durell, *Resilient Modulus Testing of Materials from Mn/Road Phase 1*, Minnesota Road Research Project, CRREL Report 96-19, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Sep. 1996.

Bigi, S.R. and R.L. Berg, *Material Testing and Initial Pavement Design Modeling*, *Minnesota Road Research Project*, CRREL Report 96-14, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Sep. 1996.

Borden, R.H., C.N. Aziz, W.M. Lowder, and N.P. Khosla, "Evaluation of Pavement Subgrade Support Characteristics by Dilatometer Test," *Transportation Research Record 1022*, Transportation Research Board, National Research Council, Washington, D.C., 1985, pp. 120–127.

Brickman, A., "An Overview of Resilient Modulus Test Systems," Workshop on Resilient Modulus, Corvallis, Ore., Mar. 1989.

Brown, S.F., "Repeated Load Testing of a Granular Material," *Journal of the Geotechnical Engineering Division*, Vol. 100, No. 7, 1974, pp. 825–841.

Brown, S.F., "Soil Mechanics in Pavement Engineering," 36th Rankine Lecture of the British Geotechnical Society, *Geotechnique,* Vol. 46, No. 3, 1996, pp. 383–426.

Burczyk, J.M., K. Ksaibati, R.A. Sprecher, and M.J. Farrar, "Factors Influencing Determination of a Subgrade Resilient Modulus Value," *Transportation Research Record 1462*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 72–78.

Burmister, D.M., "The Theory of Stresses and Displacements in Layered Systems and Application to the Design of Airport Runways," In *Proceedings of the Highway Research Board,* Vol. 23, National Research Council, Washington, D.C., 1943, pp. 125–148.

Buu, T., *Correlation of Resistance R-value and Resilient Modulus of Idaho Subgrade Soils*, Division of Highways, Idaho Department of Transportation, Boise, 1980.

Byers, C.C., M.F. Saleh, and B.D. Pidwerbesky, "Evaluation of Melter Slag as a Base Course Material," *International Journal of Pavement Engineering,* Vol. 5, No. 4, Dec. 2004, pp. 193–199.

Carmichael, R.F., III and E. Stuart, "Predicting Resilient Modulus: A Study to Determine the Mechanical Properties of Subgrade Soils," *Transportation Research Record 1043*, Transportation Research Board, National Research Council, Washington, D.C., 1985, pp. 145–148.

Claros, G., W.R. Hudson, and K.H. Stokoe, "Modifications of Resilient Modulus Testing Procedure for Equipment Calibration," *Transportation Research Record 1278*, Transportation Research Board, National Research Council, Washington, D.C., 1990, pp. 51–62.

Chai, G. and N. Roslie, "The Structural Response and Behavior Prediction of Subgrade Soils Using Falling Weight Deflectometer in Pavement Construction," *Proc., 3rd International Conference on Road and Airfield Pavement Technology,* Beijing, China, Apr. 1998.

Chen, D.-H., M.M. Zaman, and J.G. Laguros, "Resilient Moduli of Aggregate Materials: Variability Due to Testing Procedures and Aggregate Type," *Transportation Research Record 1462*, Transportation Research Board, National Research Council, Washington, D.C., 1994.

Chen, D.-H., M. Zaman, and J. Laguras, "Characterization of Base/Subbase Materials Under Repetitive Loading," *Journal of Testing and Evaluation*, Vol. 23, No. 3, 1995, pp. 180–188.

Chen, D.-H., J.N. Wang, and J. Bilyen, "Application of the DCP in Evaluation of Base and Subgrade Layers," *Transportation Research Record 1764*, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 1–10.

Chen, D.-H., D.F. Lin, P.H. Liau, and J. Bilyen, "A Correlation Between Dynamic Cone Penetrometer Data and Pavement Layer Moduli," *Geotechnical Testing Journal*, Vol. 28, No. 1, 2007, pp. 42–49.

Chen, J.Z., H. Mustaque, and M.T. LaTorella, "Use of Falling Weight Deflectometer and Dynamic Cone Penetrometer in Pavement Evaluation," *Transportation Research Record 1655*, Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 145–151.

Choubane, B. and R.L. McNamara, *Flexible Pavement Embankment Moduli Using Falling Weight Deflectometer* (*FWD*) *Data*, Research Report FL/DOT/SMO/00-442, State Materials Office, Florida Department of Transportation, Tallahassee, 2000.

Cosentino, P. and Y. Chen, "Correlating Resilient Moduli from Pressuremeter Tests to Laboratory California Bearing Ratio Tests," *Transportation Research Record 1309*, Transportation Research Board, National Research Council, Washington, D.C., 1991, pp. 56–65.

Dai, S. and C. Kremer, *Improvement and Validation of MnDOT Specification for Aggregate Base Material and Select Granular,* Report MN/RC-2005-32, Minnesota Department of Transportation, Minneapolis, Jan. 2006.

Daleiden, J.F., B.M. Killingsworth, A.L. Simpson, and R.A. Zamora, "Analysis of Procedures for Establishing in Situ Subgrade Moduli," *Transportation Research Record 1462*, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp. 102–107.

Davich, P., F. Camargo, B. Larsen, R. Roberson, and J. Siekmeier, *Validation of DCP and LWD Moisture Specifications for Granular Materials*, Report No. MN/RC-2006-20, Office of Materials, Minnesota Department of Transportation, Minneapolis, Aug. 2004a.

Davich, P., J. Labuz, B. Guzina, and A. Drescher, *Small Strain and Resilient Modulus Testing of Granular Soils*, Report No. 2004-39, Minnesota Department of Transportation, University of Minnesota, Minneapolis, Aug. 2004b.

Dawson, A.R., N.H. Thom, and J.L. Paute, "Mechanical Characteristics of Unbound Granular Materials as a Function of Condition, Flexible Pavements," *Proc., European Symposium Euroflex,* 199, A.G. Correia, Ed., Balkema, Rotterdam, the Netherlands, 1996, pp. 35–44.

De Beer, M., and C.J. van der Merwe, *Use of the Dynamic Cone Penetrometer* (*DCP*) *in the Design of Road Structures*, Minnesota Department of Transportation, St. Paul, 1991.

Drumm, E.C., Y. Boateng-Poku, and T. Johnson Pierce, "Estimation of Subgrade Resilient Modulus from Standard Tests," *Journal of Geotechnical Engineering,* Vol. 116, No. 5, 1990, pp. 774–789.

Drumm, E.C., J.S. Reeves, M.R. Madgett, and W.D. Trolinger, "Subgrade Resilient Modulus Correction for

Saturation Effects," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 7, 1997, pp. 663–670.

Dunlap, W.S., *A Report on a Mathematical Model Describing the Deformation Characteristics of Granular Materials*, Technical Report 1, Project 2-8-62-27, Texas Transportation Institute, Texas A&M University, College Station, 1963.

Edil, T. and C. Benson, *Investigation of the DCP and SSG as Alternative Methods to Determine Subgrade Stability*, SPR No. 0092-01-05, University of Wisconsin–Madison, Sep. 2005.

Edil, T., C. Benson, and A. Sawangsuriya, *Resilient Behavior of Unsaturated Subgrade Soils*, Interim Report to University of Minnesota, University of Wisconsin–Madison, Dec. 2006.

Elliot, R.P., "Selection of Subgrade Modulus for AASHTO Flexible Pavement Design," *Transportation Research Record 1354*, Transportation Research Board, National Research Council, Washington, D.C., 1992.

Elliot, R.P., S.I. Thorton, K.Y. Foo, K.W. Siew, and R. Woodbridge, *Resilient Properties of Arkansas Subgrades*, Final Report, TRC-94, Arkansas Highway and Transportation Research Center, University of Arkansas, Fayetteville, 1988.

Farrar, M.J. and J.P. Turner, *Resilient Modulus of Wyoming Subgrade Soils*, MPC Report No. 91-1, Mountain Plains Consortium, Fargo, N.D., 1991.

Federal Highway Administration, Long-Term Pavement Performance Products (CD-ROM), containing three videos on resilient modulus test procedures, 2006 [Online]. Available: www.fhwa.dot.gov/pavement/ltpp/pubs/06119/index.cfm.

Fleming, P.R., C.D.F. Rogers, A.R. Dawson, and M.W. Frost, "Subgrade Equilibrium Water Content and Resilient Modulus for U.K. Clays," *Proc., International Symposium on Subdrainage in Road Pavements and Subgrades*, World Road Association, Granada, Spain, 1998, pp. 359–366.

Frost, M.W., P.R. Fleming, and C.D.F. Rogers, "Cyclic Triaxial Tests on Clay Subgrades for Analytical Pavement Design," *Journal of Transportation Engineering*, Vol. 130, No. 3, May 1, 2004, pp. 378–386.

Gandara, J.A., A. Kancherla, G. Alvarado, S. Nazarian, and T. Scullion, *Impact of Aggregate Gradation on Base Material Performance*, TxDOT Research Report TX-1502-2, Center for Transportation Infrastructure System, University of Texas at El Paso, Nov. 2005.

George, K.P., *Prediction of Resilient Modulus from Soil Index Properties*, Final Report, University of Mississippi, in cooperation with the Mississippi Department of Transportation, U.S. Department of Transportation, and Federal Highway Administration, Oxford, Nov. 2004.

George, K.P. and W. Uddin, *Subgrade Characterization for Highway Design*, Final Report, University of Mississippi, in cooperation with the Mississippi Department of Transportation, U.S Department of Transportation, and Federal Highway Administration, Oxford, 2000.

Gudishala, R., *Development of Resilient Modulus Prediction Models for Base and Subgrade Pavement Layers from In Situ Devices Test Results*, Master's thesis, Louisiana State University, Baton Rouge, 2004.

Gupta, S., A. Ranaivoson, T. Edil, C. Benson, and A. Sawangsuriya, *Pavement Design Using Unsaturated Soil Technology*, Report No. MN/RC-2007-11, Final Research Report submitted to Minnesota Department of Transportation, University of Minnesota, Minneapolis, May 2007.

Han, Y., T.M. Petry, and D.N. Richardson, Resilient Modulus Estimation for Fine Grained Soils (CD-ROM), Presented at the 85th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 22–26, 2006.

Hassan, A., *The Effect of Material Parameters on Dynamic Cone Penetrometer Results for Fine-grained Soils and Granular Materials*, Ph.D. dissertation, Oklahoma State University, Stillwater, 1996.

Heukelom, W. and A.J.G. Klomp, "Dynamic Testing as a Means of Controlling Pavements Durinf and After Construction," *International Conference on the Structural Design of Asphalt Pavements*, Ann Arbor, Mich., 1962.

Hicks, R.G. and C.L. Monismith, "Factors Influencing the Resilient Response of Granular Materials," *Highway Research Record 345*, Highway Research Board, Washington, D.C., 1971, pp. 15–31.

Hoffmann, O.J.-M., B.B. Guzina, and A. Drescher, "Stiffness Estimates Using Portable Deflectometer," *Transportation Research Record 1869*, Transportation Research Board, National Research Council, Washington, D.C., 2004, pp. 59–66.

Hopkins, T., T.L. Beckham, C. Sun, and B. Ni, *Resilient Modulus of Kentucky Soils*, Final Research Report for Kentucky Transportation Cabinet, Kentucky Transportation Center, University of Kentucky, June 2004.

Huang, Y.H., *Pavement Analysis and Design*, Prentice Hall, Inc., Englewood Cliffs, N.J., 1993.

Hudson, J.M., E.C. Drumm, and M. Madgett, *Design Handbook for the Estimation of Resilient Response of Fine-Grained Subgrades*, Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields, University of Minnesota, Minneapolis, Vol. 2, 1994, pp. 917–931.

Hull, T., T.S. Vinson, and R.G. Hicks, "Resilient Properties of Volcanic Materials," *Proceedings, 18th Annual Symposium on Engineering Geoolgy and Soils Engineering*, Boise, Idaho, Apr. 1980.

Huoo-Ni, S., *Dynamic Properties of Sand Under True Triaxial Stress States from Resonant Column/Torsional-Shear Tests*, Ph.D. dissertation, The University of Texas, Austin, 1987.

Irwin, L.H., "Report of the Discussion Group on Practical Limitations and What Can Be Done to Overcome Them," *Transportation Research Record 1377*, Transportation Research Board, National Research Council, Washington, D.C., 1995.

Irwin, L.H., "The Search for Suitable Laboratory Test Procedures and Materials Models for Mechanistic Design, Power Point Presentation, n.d.

Ishibashi, I., L.H. Irwin, and W.-S. Lee, *Resilient Behavior of Base and Subgrade Materials*, Geotechnical Engineering Report 84-4 and Cornell Local Roads Program Report 84-2, School of Civil and Environmental Engineering and Department of Agricultural Engineering, Cornell University, Ithaca, N.Y., Aug. 1984.

Janoo, V.C., J. Bayer, G.D. Durrell, and C.E. Smith, *Resilient Modulus for New Hampshire Subgrade Soils for Use in Mechanistic Pavement Design*, ERDC/CRREL 99-14, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1999.

Janoo, V., J.J. Bayer, and C.C. Benda, "Effect of Aggregate Angularity on Base Material Properties," *Journal of Materials in Civil Engineering*, Vol. 16, No. 6, Dec. 2004, pp. 614–622.

Jones, M.P. and M.W. Witczak, "Subgrade Modulus on the San Diego Test Road," *Transportation Research Record 641*, Transportation Research Board, National Research Council, Washington, D.C., 1972, pp. 1–6.

Kalcheff, I.V. and R.G. Hicks, "A Test Procedure for Determining Resilient Properties of Granular Materials," *ASTM Journal of Testing and Material Evaluation*, Vol. 1, No. 6, 1973, pp. 472–479.

Kim, W. and J.F. Labuz, *Resilient Modulus and Strength of Base Course with Recycled Bituminous Material*, Final Report No. MN/RC-2007-05, Submitted to Minnesota Department of Transportation, University of Minnesota, Minneapolis, 2007.

Ksaibati, K., M.L. Whelan, J. Burczyk, and M.J. Farrar, *Section of Subgrade Modulus for Pavement Overlay Design Procedures*, Wyoming Department of Transportation, University of Wyoming, Laramie, Aug. 1994.

Ksaibati, K., J. Armaghani, and J. Fisher, "Effect of Moisture on Modulus Values of Base and Subgrade Materials," *Transportation Research Record 1716*, Transportation Research Board, National Research Council, Washington, D.C., 2000, pp. 20–29.

Lee, W., N.C. Bohra, A.G. Altschaeffl, and T.D. White, "Resilient Modulus of Cohesive Soils," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 2, Feb. 1997, pp. 131–136.

Lenke, L.R., R.G. McKeen, and M. Grush, *Evaluation of a Mechanical Stiffness Gauge for Compaction Control of Granular Media*, Report NM99MSC-07.2, New Mexico State Highway and Transportation Department, Albuquerque, 2001.

Lenke, L.R., R.G. McKeen, and M.P. Grush, "Laboratory Evaluation of the GeoGauge for Compaction Control," *Transportation Research Record 1849*, Transportation Research Board, National Research Council, Washington, D.C., 2003, pp. 20–30.

Lekarp, F. and A.R. Dawson, "Modeling Permanent Deformation Behavior of Unbound Granular Materials," *Construction Building Materials*, Vol. 12, No. 1, 1998, pp. 9–18.

Manual of Contract Documents for Highway Works (MCHW), Specification for highway works, Vol. 1, HMSO, London, U.K., 1994.

Leksø, S., et al., Implementation of Falling Weight Deflectometer Technology and Development of Analytical Pavement Design in Thailand, *Proceedings of the 9th International Conference of Asphalt Pavements*, International Society for Asphalt Pavements, Copenhagen, Denmark, Aug. 17–22, 2002.

Li, D. and E.T. Selig, "Resilient Modulus for Finegrained Subgrade Soils," *Journal of Geotechnical Engineering*, Vol. 120, No. 6, 1994, pp. 939–957.

Maher, M.H., W.J. Papp, Jr., and N. Gucunski, "Measurement of Soil Resilient Properties Using Noncontacting Proximity Sensors," *Transportation Research Record 1584*, Transportation Research Board, National Research Council, Washington, D.C., 1996.

Maher, M.H., T. Bennett, W.J. Papp, Jr., and N. Gucunski, *Resilient Modulus Properties of New Jersey Subgrade Soils*, FHWA NJ 2000-01, Rutgers University, Piscataway, N.J., Sep. 2000.

Malla, R.B. and S. Joshi, *Establish Subgrade Support Values for Typical Soils in New England*, Report No. NETCR 57, New England Transportation Consortium, Fall River, Mass., Apr. 2006.

Masada, T., S.M. Sargand, B. Abdalla, and J.L. Figueros, *Material Properties for Implementation of Mechanistic-Empirical* (*ME*) *Pavement Design Procedures*, Final Report, Ohio Department of Transportation, Ohio Research Institute for the Transportation and Environment, Athens, 2004.

Meigh, A.C., "Cone Penetrating Testing—Methods and Interpretation," CIRIA, Butterworths Publishers, Markham, ON, Canada, 1987.

Meshkani, A., I. Abdallah, and S. Nazarian, *Determination of Non-Linear Parameters of Flexible Pavement Layers from Non-Destructive Testing*, Research Report, TX 1780-3, Center for Transportation Infrastructure Systems, The University of Texas at El Paso, Apr. 2004.

Mohammad, L.N., A.J. Puppala, and P. Alavilli, "Influence of Testing Procedure and LVDTs Location on Resilient Modulus of Soils," *Transportation Research Record 1462*, Transportation Research Board, National Research Council, Washington, D.C., 1994a, pp. 91–101.

Mohammad, L.N., A.J. Puppala, and P. Alavilli, *Investigation of the Use of Resilient Modulus for Louisiana Soils in Design of Pavements*, Final Report No. 283, Louisiana Transportation Research Center, Federal Highway Administration, Louisiana Department of Transportation and Development, June 1994b.

Mohammad, L.N., A.J. Puppala, and P. Alavilli, Resilient Properties of Laboratory Compacted Subgrade Soils," *Transportation Research Record 1504*. Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 87–102.

Mohammad, L.N., B. Huang, A.J. Puppala, and A. Allen, "Regression Model for Resilient Modulus of Subgrade Soil," *Transportation Research Record 1687*, Transportation Research Board Record, National Research Council, Washington, D.C., 1999, pp. 47–54.

Mohammad, L.N., H.H. Titi, and A. Herath, *Investigation of the Applicability of Intrusion Technology to Estimate the Resilient Modulus of Subgrade Soil*, FHWA/LA-00/332, Louisiana Transportation Research Center, Baton Rouge, 2000.

Mohammad, L.N., H.H. Titi, and A. Herath, *Effect of Moisture Content and Dry Unit Weight on the Resilient Modulus of Subgrade Soils Predicted by Cone Penetration Test*, FHWA/LA-00/355, Louisiana Transportation Research Center, Baton Rouge, 2002.

Mohammad, L.N., K. Gaspard, A. Herath, and M. Nazzal, *Comparative Evaluation of Subgrade Resilient Modulus from Non-Destructive, In-Situ and Laboratory Methods*, FHWA/LA-06/417, Louisiana Transportation Research Center, Baton Rouge, 2007.

Moravec, M., Personal communication, 2007, "Transportaton Pooled Fund Program" [Online]. Available: http://www.pooledfund.org/projectdetails.asp?id=1140&status=1.

Nataatmadja, A., "Resilient Modulus of Granular Materials Under Repeated Loading," *Proc., 7th International Conference on Asphalt Pavements*. University of Nottingham, Nottingham, UK, Vol. 1, 1992, pp. 172–185.

Nataatmadja, A., "On the Response of Granular Unbound Pavement Materials Under Repeated Loading," *Proc., 17th Australia Road Research Board Conference*, Gold Coast, Australia, Vol. 2, 1994, pp. 99–114.

Nataatmadja, A., and Y.L. Tan, "Resilient Response of Recycled Concrete Road Aggregates," Technical Note No. 22318, *Journal of Transportation Engineering*, Vol. 127, No. 5, Sep./Oct. 2001.

National Cooperative Highway Research Program, *Recommended Standard Method for Routine Resilient Modulus Testing of Unbound Granular Base/Subbase Materials and Subgrade Soils*, *Protocol 1-28A*, Transportation Research Board, National Research Council, Washington, D.C., 2002.

Nazarian, S., *Feasibility Study on Improvements to Dynamic Cone Penetrometer*, Research Report 3903-2, Center for Highway Materials Research, University of Texas at El Paso, 1998.

Nazarian, S., *Quality Management of Flexible Pavement Layers with Seismic Methods: Test Methods*, Research Report 5-1735-01-P5, Center for Highway Materials Research, University of Texas at El Paso, Nov. 2006.

Nazarian, S., M. Baker, and K. Crain, "Use of Seismic Pavement Analyzer in Pavement Evaluation," *Transportation Research Record 1505*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 1–8.

Nazarian, S., R. Pezo, and M. Picronell, *Testing Methodology for Resilient Modulus of Base Materials*, Research Report 1336-1, Center for Geotechnical and Highway Materials Research, University of Texas at El Paso, 1996.

Nazarian, S., J. Rojas, R. Pezo, D. Yuan, I. Abdallah, and T. Scullion, "Relating Laboratory and Field Moduli of Texas Base Materials," *Transportation Research Record 1639*, Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 1–11.

Nazarian, S., D. Yuan, V. Tandon, and M. Arrellano, *Quality Management of Flexible Pavement Layers with Seismic Methods*, Research Report 1735-3F, Center for Highway Materials Research, University of Texas at El Paso, 2003.

Nazarian, S., D. Yuan, and V. Tandon, *Quality Management of Flexible Pavement Layers with Seismic Methods*, Research Report 0-1735-S, Center for Transportation Infrastructure Systems, University of Texas at El Paso, 2005.

NCHRP Research Results Digest 285: Laboratory Determination of Resilient Modulus for Flexible Pavement Design, Transportation Research Board, National Research Council, Washington, D.C., Jan. 2004, 48 pp.

NCHRP Research Results Digest 307: Identification of Liability-Related Impediments to §409 Safety Data Among Transportation Agencies and a Synthesis of Best Practices, Transportation Research Board, National Research Council, Washington, D.C., Sep. 2006, 32 pp.

NCHRP Research Results Digest 308: *Changes to Mechanistic Empirical Pavement Design Guide Software Through Version 0.900, July 2006*, Transportation Research Board, National Research Council, Washington, D.C., Sep. 2006, 22 pp.

Nelson, C.R., D.L. Petersen, R.L. Peterson, J.C. Rudd, and E. Sellman, Design and Compaction Control for Foundation Soil Improvements, T.H. 61 Reconstruction, New Port, Minnesota (CD-ROM), Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 11–15, 2004.

Newcomb, D.E. and B. Birgisson, *NCHRP Synthesis of Highway Practice 278: Measuring In-Situ Mechanical Properties of Pavement Subgrade Soils*, Transportation Research Board, National Research Council, Washington, D.C., 1999.

Ni, B., T.C. Hopkins, L. Sun, and T.L. Beckham, "Modeling the Resilient Modulus of Soils," *Proceedings of the 6th International Conference on the Bearing Capacity of Roads, Railways, and Airfields*, Vol. 2, A.A. Balkema Publishers, Rotterdam, the Netherlands, pp. 1131–1142.

Ohio Department of Transportation Pavement Design Manual, Columbus, Ohio [Online]. Available: www.dot.state.oh.us/pavement/Pubs.

Oloo, S.Y. and D.G. Fredlund, "The Application of Unsaturated Soil Mehcanics Theory to the Design of Pavements," *Proceedings of the Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Trondheim, Norway, pp. 1419–1428.

Ooi, P.S.K., K.G. Sandefur, and A.R. Archilla, *Correlation of Resilient Modulus of Fine-Grained Soils with Common Soil Parameters for Use in Design of Flexible Pavements*, Report No. HWY-L-2000-06, Hawaii Department of Transportation, Honolulu, 2006.

Petersen, J.S., S.A. Romanoschi, M.A. Onyango, and M. Hossain, Evaluation of Prima Light Falling Weight Deflectometer as Quality Control Tool for Compaction of Fine Grained Soils (CD-ROM), Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 21–25, 2007.

Petersen, L. and R. Peterson, *Intelligent Compaction and In-Situ Testing at MN/DOT TH53*, MnDOT Report MN/RC-2006-13, CNA Consulting Engineers, Minneapolis, Minn., 2006.

Pezo, R.F., A General Method of Reporting Resilient Modulus Tests of Soils: A Pavement Engineer's Point of View, Presented at the 72nd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1993.

Pezo, R.F. and W.R. Hudson, "Prediction Models of Resilient Modulus for Nongranular Materials," *Geotechnical Testing Journal*, Vol. 17, No. 3, 1994, pp. 349–355.

Pezo, R.F., D.S. Kim, K.S. Stokoe, and W.R. Hudson, Aspects of a Reliable Resilient Modulus Testing System, Presented at the 71st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1992.

Ping, W.V. and C. Ling, *Enhancement of Resilient Modulus Data for the Design of Pavement Structures in Florida*, Research Report No. FL/DOT/RMC/BD-543-4, Department of Civil Engineering, FAMU–FSU College of Engineering, Tallahassee, Fla., Sep. 2007.

Ping, W.V., E. Wu, and Z. Yang, *Application of Noncontacting Proximity Sensors for Measuring Soil Resilient Characteristics*, Research Report No. FL/DOT/RMC/ 0510815, Department of Civil Engineering, FAMU–FSU College of Engineering, Tallahassee, Fla., Sep. 2000.

Ping, W.V., Z. Yang, and Z. Gao, "Field and Laboratory Determination of Granular Subgrade Moduli," *Journal of Performance of Constructed Facilities*, Vol. 16, No. 4, Nov. 1, 2002, pp. 149–159.

Ping, W.V., W. Xiong, and Z. Yang, *Implementing Resilient Modulus Test for Design of Pavement Structures in Florida*, Research Report No. FL/DOT/RMC/BC-352-6, Department of Civil Engineering, FAMU–FSU College of Engineering, Tallahassee, Fla., Sep. 2003.

Powell, W.D., J.F. Potter, H.C. Mayhew, and M.E. Nunn, *The Structural Design of Bituminous Roads*, TRRL Report LR 1132, Department of Transport, Berkshire, U.K., 1984.

Puppala, A.J., L.N. Mohammad, and A. Allen, "Engineering Behavior of Lime Treated Louisiana Subgrade Soil," *Transportation Research Record 1546*, Transportation Research Board, National Research Council, Washington, D.C., 1997, pp. 24–31.

Puppala, A.J., L.N. Mohammad, and A. Allen, "Permanent Deformation Characterization of Subgrade Soils from RLT Test," *Journal of Materials in Civil Engineering*, Vol. 11, No. 4, Nov. 1999, pp. 274–282.

Rada, G. and M.W. Witczak, "Comprehensive Evaluation of Laboratory Resilient Moduli Results for Granular Materials," *Transportation Research Record 810*, Transportation Research Board, National Research Council, Washington, D.C., 1981, pp. 23–33.

Rahim, A.A. and K.P. George, "Falling Weight Deflectometer for Estimating Subgrade Elastic Moduli," *Journal of Transportation Engineering*, Vol. 129, No. 1, Jan. 2003, pp. 100–107.

Richart, F.E., "Some Effects of Dynamic Soil Properties on Soil-Structure Interaction," *Journal of Geotechnical Engineering Division*, Vol. 101, No. 12, 1975, pp. 1193–1240.

Richter, C., "Seasonal Variations in the Moduli of Unbound Pavement Layers," Publication No. FHWA-HRT-04-079, Turner–Fairbanks Highway Research Center, McLean, Va., 2006.

Saeed, A., J.W. Hall, and W. Barker, *NCHRP Report 453: Performance Related Tests of Aggregates for Use in Unbound Pavement Layers*, Transportation Research Board, National Research Council, Washington, D.C., 2001.

Salgado, R. and S. Yoon, *Dynamic Cone Penetration Test for Subgrade Assessment*, Research Report FHWA/IN/JTRP-2002/30, Purdue University, West Lafayette, Ind., 2003.

Santha, B.L., "Resilient Modulus of Subgrade Soils: Comparison of Two Constitutive Equations," *Transportation Research Record 1462*, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp. 79–90.

Sawangsuriya, A., T. Edil, and P. Bosscher, Laboratory Evaluation of the Soil Stiffness Gauge. Presented at the 81st Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 13–17, 2002.

Seed, H.B. and R.L. McNeill, "Soil Deformation Under Repeated Stress Applications," *ASTM Special Technical Publication*, No. 32, 1958, pp. 177–197.

Seed, H.B., C.K. Chan, and C.E. Lee, "Resilience Characteristics of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavements," *Proc., International Conference on the Structural Design of Asphalt Pavements*, University of Michigan, Ann Arbor, 1962, pp. 611–636.

Seed, H.B., F.G. Mitry, C.L. Monismith, and C.K. Chan, *NCHRP Report 35: Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests*, Highway Research Board, National Research Council, Washington, D.C., 1967.

Shook, J.F., F.N. Finn, M.W. Witczak, and C.L. Monismith, "Thickness Design of Asphalt Pavements—The Asphalt Institute Method," *Proc., 5th International Conference on the Structural Design of Asphalt Pavements*, Vol. 1, the Netherlands, 1982, pp. 17–44.

Siekmeier, J., *In Situ Testing for Mechanistic Empirical Pavement Design*, OMRR Research Seminar, Minnesota Department of Transportation, PowerPoint Presentation, Aug. 2002.

Siekmeier, J.A., D. Young, and D. Beberg, "Comparison of the Dynamic Cone Penetrometer with Other Tests During Subgrade and Granular Base Characterization in Minnesota," In *Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume, ASTM Special Technical Publication*, No. 1375, S.D. Tayabji and E.O. Lukanen, Eds., American Society for Testing and Materials, West Conshohocken, Pa., 1999.

Simonsen, E., V.C. Janoo, and U. Sacsson, "Resilient Properties of Unbound Road Materials during Seasonal Frost Conditions," *Journal of Cold Regions Engineering*, Vol. 16, No. 1, Mar. 2002, pp. 28–50.

Steinart, B.C., D.N. Humphrey, and M.A. Kestler, *Portable Falling Weight Deflectometer Study*, New England Transportation Consortium Project No. 00-4, University of Maine, Orono, 2005, 331 pp.

Stokoe, K.H., II, D.-S. Kim, and R.D. Andrus, "Development of Synthetic Specimens for Equipment Calibration," *Transportation Research Record 1278*, Transportation Research Board, National Research Council, Washington, D.C., 1990, pp. 63–81.

Swenson, J., B. Guzina, J.F. Labuz, and A. Drescher, *Moisture Effects on PVD and DCP Measurements*, Report No. MN/RC-2006-26, Submitted to Minnesota Department of Transportation, University of Minnesota, Minneapolis, 2006.

Terrel, R.L., I.S. Awad, and L.R. Foss, "Techniques for Characterizing Bituminous Materials using a Versatile Triaxial Testing System," *ASTM Special Technical Publication*, No. 561, 1974, pp. 47–66.

Theyse, H.L., M. de Beer, and F.C. Rust, "Overview of the South African Mechanistic Pavement Design Analysis Method," Preprint, 75th Annual Meeting of the Transportation Research Board, Jan. 1996, Washington, D.C.

Thompson, M.R. and R.P. Elliot, "ILLI-PAVE-Based Response Algorithms for Design of Conventional Flexible Pavements," *Transportation Research Record 1043*, Transportation Research Board, National Research Council, Washington, D.C., 1985, pp. 50–57.

Thompson, M.R. and T.G. LaGrow, *A Proposed Conventional Flexible Pavement Thickness Design Procedure*, FHWA-IL-UI-223. Illinois University, Urbana–Champaign, Dec. 1988, 47 pp.

Thompson, M.R. and Q.L. Robnett, *Resilient Properties of Subgrade Soils*. Final Report—Data Summary, Transportation Engineering Series 14, Illinois Cooperative Highway Research and Transportation Program Series, University of Illinois, Urbana, 1976.

Thompson, M.R. and Q.L. Robnett, "Resilient Properties of Subgrade Soils," *Transportation Engineering Journal*, Vol. 105, No. TE1, 1979, pp. 71–89.

Thompson, M.R. and K.L. Smith, "Repeated Triaxial Characterization of Granular Bases," *Transportation Research*

Record 1278, Transportation Research Board, National Research Council, Washington, D.C., 1990.

Titi, H., B. Elias, and S. Helwany, *Determination of Typical Resilient Modulus Values for Selected Soils in Wisconsin*, SPR 0092-03-11, Wisconsin Department of Transportation, University of Wisconsin, Milwaukee, May 2006.

Titus-Glover, L. and E.B. Fernando, *Evaluation of Pavement Subgrade Material Properties and Test Procedures*, Final Report No. FHWA/TX-96/1335-2, Texas Transportation Institute, Texas A&M University, College Station, Nov. 1995.

Tutumluer, E. and M.R. Thompson, "Anisotropic Modeling of Granular Bases in Flexible Pavements," *Transportation Research Record 1577*, Transportation Research Board, National Research Council, Washington, D.C., 1997, pp. 18–26.

Uzan, J., "Characterization of Granular Materials," *Transportation Research Record 1022*, Transportation Research Board, National Research Council, Washington, D.C., 1985, pp. 52–59.

Uzan, J., "Permanent Deformation in Flexible Pavements," *Journal of Transportation Engineering*, Vol. 130, No. 1, Jan. 2004, pp. 6–13.

Vinson, T.S., *Fundamentals of Resilient Modulus Testing. Workshop on Resilient Modulus*, Corvallis, Ore., 1989, 51 pp.

Von Quintus, H. and B. Killingsworth, *Analyses Relating to Pavement Material Characterizations and Their Effects on Pavement Performance*, FHWA-RD-97-085, Federal Highway Administration, McLean, Va., 1998.

Vuong, B.T., *Improved Performance-Based Material Specifications and Performance Prediction Models for Granular Pavements*, Ph.D. dissertation, Department of Civil and Geological Engineering, Faculty of Engineering, RMIT University, Melbourne, July 2001.

Vuong, B.T. and D. Hazell, "Development of Performance-Based Specifications for Unbound Granular Materials: Issues and Recommendations," *Road and Transport Research*, Dec. 2003.

White, D., M.R. Thompson, and P. Vennapusa, *Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials*, Minnesota Department of Transportation, Center for Transportation Research and Education, Iowa State University, Ames, Apr. 2007.

Wilson, B.E., S.M. Sargand, G.A. Hazen, and R. Green, "Multiaxial Testing of Subgrade," *Transportation Research Record 1278*, Transportation Research Board, National Research Coucnil, Washington, D.C., 1990, pp. 91–95

Witczak, M.W. and J. Uzan, *The Universal Airport Pavement Design System*, Report 1 of 4, Granular Material Characterization, University of Maryland, College Park, 1988.

Witzack, M., X. Qi, and M.W. Mirza, "Use of Nonlinear Subgrade Modulus in AASHTO Design Procedures," *Journal of Transportation Engineering*, Vol. 121, No. 3, May/June 1995, pp. 273–282.

Wolfe, W.E. and T.S. Butalia, *Seasonal Instrumentation of SHRP Pavements*, Final Report for Ohio Department of Transportation, Ohio State University, Columbus, 2004.

Woolstrum, G., "Dynamic Testing of Nebraska Soils and Aggregates," *Transportation Research Record 1278*, Transportation Research Board, National Research Council, Washington, D.C., 1990, pp. 27–34.

Yau, A. and H. Von Quintus, *Study of LTPP Laboratory Resilient Modulus Test Data and Response Characteristics*, Report No. FHWA-RD-02-051, Federal Highway Administration, McLean, Va., Oct. 2002.

Yau, A. and H. Von Quintus, "Predicting Elastic Response Characteristics of Unbound Materials and Soils," *Transportation Research Record 1874*, Transportation Research Board, National Research Council, Washington, D.C., 2004, pp. 47–56.

Zaman, M., D.-H. Chen, and J. Laguros, "Resilient Modulus of Granular Materials," *Journal of Transportation Engineering*, Vol. 120, No. 6, 1994, pp. 967–988.

Zhang, Z.J., Y.M. Abu-Farsakh, and L. Wang, Evaluation of Trench Backfill at Highway Cross-Drain Pipes, Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 11–15, 2004.

APPENDIX A

SURVEY QUESTIONNAIRE

QUESTIONNAIRE

NCHRP PROJECT 20-5

TOPIC 38-09 FY 2006

ESTIMATING RESILIENT MODULUS VALUES OF SUBGRADES AND UNBOUND PAVEMENT MATERIALS

Background and Purpose

The new *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) and 1993 AASHTO Pavement Design Guide are founded on the use of resilient modulus as the primary input parameter when characterizing subgrade, subbase, and base materials. Resilient modulus values of these materials are typically determined either by performing repeated load triaxial tests in the laboratory or by conducting nondestructive tests in the field or using correlations relating moduli to basic soil properties or other material parameters. For over 30 years, researchers and practitioners from various departments of transportation (DOTs) have been developing and revising existing methods for better estimation of resilient moduli properties.

One of the main objectives of Synthesis Topic 38-09 is to gather information on how various agencies determine resilient moduli of subgrades and unbound bases and how these properties have been used in the design of pavement systems. To accomplish this objective, the following questionnaire is designed in three parts. Part II should be completed by the state Materials/Geotechnical engineer or agency official most knowledgeable about the agency's material testing practices, and Part III should be completed by the Pavement Design engineer or agency official most knowledgeable about pavement design practices.

PART I. RESPONDENT INFORMATION

1. Which division is in charge of determining the resilient moduli of base and subgrade material for pavement design within the agency?

   Division:

   DOT:

2. Who is in charge of research or technical support/assistance or pavement design, which provides a "troubleshooting" for pavement performance problems and involves in the pavement design within the agency?

   Division (Research/Technical Support):

   Division (Pavement Design):

Materials (M_R) Related Testing Information Provided by:

Name:____

Title:____

Agency: ____

Address:____

City: ________________ State:________________ Zip: ____________

Phone:________________ Fax:________________ e-mail: ____________

Pavement Design Information Provided by:

Name:____

Title:____

Agency: ____

Address:____

City: ________________ State:________________ Zip: ____________

Phone:________________ Fax:________________ e-mail: ____________

Please return the completed questionnaire by January 15, 2007, to:

Anand J. Puppala, PhD, PE

After completing the survey, if there are issues pertaining to resilient moduli of subgrades and unbound bases that you believe are not addressed by the questionnaire, please feel free to contact the author directly.

PART II. RESILIENT MODULUS: LABORATORY AND FIELD MEASUREMENTS, AND CORRELATIONS

1. In how many pavement design projects per year (average) are resilient moduli properties of subgrades and unbound bases determined/measured?

   ☐ None*

   ☐ 1–10

   ☐ 10–20

   ☐ More than 20 per year

   * *If you answered* None, *please skip the survey and provide any comments related to resilient property measurements.*

2. Please indicate the types of soil that your agency has dealt with. (Check all that apply.)

   Soil Types

   ☐ Gravel (GW, GP)

   ☐ Coarse Sand (SW, SP)

   ☐ Fine Sand (SP)

   ☐ Silty Clay (MC and others)

   ☐ Lean Clay (CL)

   ☐ Fat Clay (CH)

   Other Soil Type:

   Unbound Base Type

   ☐ Crushed Stone

   ☐ Gravel

   ☐ Crushed Concrete

   ☐ Crushed Masonry

   ☐ Lime Stone

   ☐ Others

   Other Base Type:

3. Does your agency use **laboratory methods** for the determination of resilient moduli properties? (Check all that apply.)

   ☐ Yes

   ☐ No

   If the answer is Yes, please answer the following questions. Otherwise please skip to Question 17.

IIA. LABORATORY METHODS

4. Who is responsible for performing resilient modulus (to be used for pavement design practice) laboratory tests?

   ☐ Geotechnical/Materials Lab

   ☐ University Lab (as a part of research subcontract)

   ☐ Outside Lab

   ☐ Other (explain):

5. Do you follow specific guidelines regarding the number of tests to be performed per volume of the subgrade/unbound base or length of the highway?

   Subgrade

   ☐ Yes, Please provide a few details/reference for the guidelines

   ☐ No

   Unbound Base

   ☐ Yes, Please provide a few details/reference for the guidelines

   ☐ No

6. What laboratory method is typically used?
   - ☐ Repeated load triaxial test
   - ☐ Small strain shear moduli measurements using Resonant Column test
   - ☐ Small strain shear moduli measurement using Bender Element test
   - ☐ Others (explain):

7. What procedure is followed in performing laboratory repeated load triaxial tests?
   - ☐ AASHTO T-294
   - ☐ AASHTO T-307
   - ☐ NCHRP 1-28 A Harmonized
   - ☐ TP-46
   - ☐ Others (explain):

   If the response to the above question is Others, please answer the following Question 8; otherwise, skip to Question 9.

8. Provide more details about the test procedure followed by your agency.

   Subgrade
   - ☐ Applied confining stresses (explain):
   - ☐ Applied deviatoric stresses (explain):
   - ☐ Displacement measurements (explain):
   - ☐ Please list the reference/test procedure:

   Unbound Base
   - ☐ Applied confining stresses (explain):
   - ☐ Applied deviatoric stresses (explain):
   - ☐ Displacement measurements (explain):
   - ☐ Please list the reference/test procedure (explain):

9. Provide details on the laboratory specimens used in the resilient moduli tests. (Check all that apply.)
   - ☐ Laboratory fabricated specimens for new pavement design
   - ☐ "Undisturbed" field samples for pavement rehabilitation design
   - ☐ Laboratory fabricated specimens for pavement rehabilitation design
   - ☐ Others (explain):

10. Describe the laboratory procedures followed for specimen preparation. (Check all that apply.)

   Subgrade
   - ☐ Impact compaction (similar to Proctor test methods)
   - ☐ Static compaction/compression
   - ☐ Vibratory compaction
   - ☐ Kneading compaction (Gyratory type)
   - ☐ Others (explain):

Unbound Base

☐ Impact compaction (similar to Proctor test methods)

☐ Static compaction

☐ Vibratory compaction

☐ Kneading compaction (Gyratory type)

☐ Others (explain):

11. Is any moisture conditioning of specimens performed prior to resilient modulus testing?

☐ No (basically tested at compaction moisture content conditions)

☐ Yes (please provide details):

12. How many laboratory tests are performed for each subgrade and base location to establish average moduli properties?

Subgrade

☐ 1

☐ 3

☐ Others (explain):

Unbound Base

☐ 1

☐ 3

☐ Others (explain):

13. Which regression model form is used to analyze the laboratory resilient moduli results?

☐ $M_R = k_1.\ \theta^{k2}$

☐ $M_R = k_3.\ \sigma_d^{k4}$

☐ $M_R = k_5.\ \sigma_{oct}^{k6}\tau_{OCT}^{k7}$

☐ $M_R = k_8.\ \sigma_3^{k9}\sigma_d^{k10}$

☐ Other models (please explain the number of constants and model attributes such as confining or deviatoric or octahedral stresses):

14. How do you determine the field resilient moduli (for pavement design) from the laboratory test results?

☐ Use regression model with field confining and deviatoric stresses

☐ Apply field confining and deviatoric stresses in the lab test

☐ Others (explain):

15. What are the problems of the laboratory resilient modulus tests? (Check all that apply and rate the top three of them by indicating 1, 2, 3 in the comment box next to each response.)

☐ Repeatability problems

☐ Reliability problems (accuracy of measurements)

☐ Requires skilled personnel to conduct the tests

☐ Too many standards

☐ Too much time per test

- ☐ Expensive
- ☐ Difficulty in applying tensile stresses in the lab
- ☐ Unsure whether method provides true modulus of subgrade in field
- ☐ Others (explain):

16. What are the strong points of the laboratory resilient modulus tests? (Check all that apply.)
    - ☐ Better test method
    - ☐ Laboratory response is a better indicator of field performance
    - ☐ Provides reliable structural number for pavement design
    - ☐ Others (explain):

    The following questions (Yes/No) are related to calibration and verification of the test equipment. (Check all that apply.)

    Do you perform the equipment calibration?

    - ☐ **Yes, Please provide the frequency (in terms of months or tests)**
    - ☐ **No**

    Do you use a calibrated specimen with known moduli for verification of test measurements?

    - ☐ **Yes**
    - ☐ **No**

17. Does your agency use **<u>field methods</u>** for the determination of resilient moduli properties? (Check all that apply.)
    - ☐ Yes
    - ☐ No

    If the answer is Yes, please answer the following questions. Otherwise please skip to Question 31.

IIB: FIELD NONDESTRUCTIVE TESTS

18. Check the methods used by your agency to determine the field subgrade and unbound base moduli. (Check all that apply.)
    - ☐ Falling Weight Deflectometer (FWD)
    - ☐ Dynaflect
    - ☐ GeoGauge
    - ☐ Seismic methods
    - ☐ Others:

    If the answer is FWD, please answer the following questions. Otherwise, skip to Question 25. In the case of multiple responses, please answer the following:

FWDS

19. Explain the main intent in performing field FWD tests.
    - ☐ QC/QA for indirect compaction quality evaluation for new pavement construction
    - ☐ Determination of subgrade moduli for pavement rehabilitation
    - ☐ To ensure laboratory moduli represents field moduli
    - ☐ Determination of structural coefficients of pavement layers
    - ☐ Others (explain):

20. Do you follow any specific guidelines regarding the number of FWD tests to be performed per length of the highway?

    ☐ Yes, Please provide a few details/reference for the guidelines

    ☐ No

21. Please provide the following information related to FWD tests and analysis.

    Manufacturer of FWD

    Interpretation or backcalculation software used for FWD analysis

    Responsible personnel/division for performing FWD tests (materials/pavements)

    Responsible personnel/division for analyzing FWD tests (materials/pavements)

22. Please check mark the following that can be described as limitations of FWD methods. (Check all that apply and rate the top three of them by indicating 1, 2, 3 in the comment box next to each response.)

    Subgrade

    ☐ Poor reproducibility of test results

    ☐ Calibration of geophones

    ☐ Requires skilled personnel to perform the tests,

    ☐ Requires skilled personnel to analyze the test results,

    ☐ Different moduli predictions with different software for the same data,

    ☐ Lack of availability of additional information such as depth of bedrock,

    ☐ No standard field testing protocols,

    ☐ No correlation with laboratory measured moduli,

    ☐ Too much time per test,

    ☐ Expensive,

    ☐ Other (please specify):

    Unbound Bases

    ☐ Poor reproducibility of test results,

    ☐ Calibration of geophones,

    ☐ Requires skilled personnel to perform the tests,

    ☐ Requires skilled personnel to analyze the test results,

    ☐ Different moduli predictions with different software for the same data,

    ☐ Lack of availability of additional information such as depth of bedrock,

    ☐ No standard field testing protocols,

    ☐ No correlation with laboratory measured moduli,

    ☐ Too much time per test,

    ☐ Expensive,

    ☐ Other (please specify)

23. What are the strong points of the FWD tests? (Check all that apply.)
    - ☐ Faster test method
    - ☐ Inexpensive when compared to sampling and lab tests
    - ☐ Provides results that are not affected by the boundary conditions
    - ☐ Provides reliable structural number for pavement design
    - ☐ Others (explain):

24. Do you recommend the use of your FWD backcalculation software for other DOTs for pavement layer moduli determination?
    - ☐ Yes
    - ☐ No
    - ☐ Others (explain):

25. In your agency, are there any specific guidelines on how to interpret the FWD moduli? If the answer is yes, please provide the reference details and how we can get that information.
    - ☐ Yes
    - ☐ No

    Please skip to Question 32

<u>OTHER NONDESTRUCTIVE METHODS</u> (DYNAFLECT/SEISMIC METHODS/GEOGAUGE/OTHERS)

26. Explain the main intent in performing these tests.
    - ☐ QC/QA for indirect compaction quality evaluation for new pavement construction
    - ☐ Determination of subgrade moduli for pavement rehabilitation
    - ☐ To ensure laboratory moduli represent field moduli
    - ☐ Others (explain):

27. Do you follow specific guidelines regarding the number of tests to be performed per volume of the subgrade/unbound base or length of the highway?
    - ☐ Yes, please provide a few details/reference for the guidelines
    - ☐ No

28. Do you recommend this method for other DOTs for determination of layer moduli?

    Subgrade
    - ☐ Yes
    - ☐ No
    - ☐ Others (explain):

    Unbound Base
    - ☐ Yes
    - ☐ No
    - ☐ Others (explain):

29. Please check mark the following that can be described as limitations of these methods. (Check all that apply and rate the top three of them by indicating 1, 2, 3 in the comment box next to each response.)

Subgrade

☐ Poor reproducibility of test results,

☐ Calibration of geophones,

☐ Requires skilled personnel to perform the tests,

☐ Requires skilled personnel to analyze the test results,

☐ Different moduli predictions with different software for the same data,

☐ Lack of availability of additional information such as depth of bedrock,

☐ No standard field testing protocols,

☐ No correlation with laboratory measured moduli,

☐ Too much time per test,

☐ Expensive,

☐ Other (please specify):

Unbound Bases

☐ Poor reproducibility of test results,

☐ Calibration of geophones,

☐ Requires skilled personnel to perform the tests,

☐ Requires skilled personnel to analyze the test results,

☐ Different moduli predictions with different software for the same data,

☐ Lack of availability of additional information such as depth of bedrock,

☐ No standard field testing protocols,

☐ No correlation with laboratory measured moduli,

☐ Too much time per test,

☐ Expensive,

☐ Other (please specify):

30. What are the strong points of these nondestructive tests? (Check all that apply.)

☐ Faster test method

☐ Inexpensive when compared to sampling and lab tests

☐ Provides results that are not affected by the boundary conditions

☐ Provides reliable structural number for pavement design

☐ Others (explain):

31. Overall, how do you assess the nondestructive field tests for moduli determination?

Subgrade

☐ Very good, well-established procedures

☐ Poor reproducibility problems, needs research on analysis routines

☐ Poor, requires equipment modifications

Unbound Base

☐ Very good, well-established procedures

☐ Poor reproducibility problems, needs research on analysis routines

☐ Poor, requires equipment modifications

32. Does your agency use **empirical or semi-empirical correlations** for the determination of resilient moduli properties?

☐ Yes

☐ No

If the answer is Yes, please answer the following questions. Otherwise please skip to Question 38.

IIC: CORRELATIONS

33. What type of correlations are used to determine the resilient moduli?

Subgrade

☐ Direct correlations between resilient modulus and other soil properties Ex: M_R = f (PI, % passing No.200, d_{50} etc.)

☐ Direct correlations between resilient modulus and in situ test measurements

☐ Ex: M_R = f (SPT N values or DCP or cone tip resistance)

☐ Indirect correlations using constants from regression models and soil properties

☐ Ex: k_1 or k_2 = f (PI, % passing No.200, d_{50} etc.)

☐ Others:

Unbound Base

☐ Direct correlations between resilient modulus and other soil properties

☐ Direct correlations between resilient modulus and in situ test measurements

☐ Indirect correlations using constants from regression models and soil properties

☐ Others:

34. How were these correlations developed? Please provide additional details including the reference details, if available.

☐ Not local, from the papers published in the literature

☐ Not local, from the recommended AASHTO design guide, please specify the design guide reference (1972, 1986, 1993, *MEPDG*)

☐ Not local, from others

☐ Local, developed by the database collected over several years

35. How do you characterize the level of reliability of the correlations used by your DOT?

Subgrade

☐ Very good

☐ Good

☐ Fair

☐ Poor

Unbound Base

☐ Very good

☐ Good

☐ Fair

☐ Poor

36. Do you check the correlation predictions by performing additional tests (laboratory or field nondestructive tests). If the answer is yes, please list type(s) of tests conducted for this purpose.

☐ Yes

☐ No

Subgrade

Unbound Base

37. Are the local correlations updated frequently? If the answer is yes, please specify the frequency time period for the updates.

Subgrades

☐ Yes,

☐ No

Unbound Base

☐ Yes,

☐ No

38. Overall, please check mark the following that can be described as limitations of these methods. (Check all that apply and rate the top three of them by indicating 1, 2, and 3 in the comment box next to each response.):

Subgrades

☐ Poor predictions,

☐ Correlations developed from a limited database,

☐ Too complex, should be simplified,

☐ Too simple and should contain normalized stress parameters/constants,

☐ No proper protocols on how to use or evaluate them,

Unbound Base

☐ Poor predictions,

☐ Correlations developed from a limited database,

☐ Too complex, should be simplified,

☐ Too simple and should contain normalized stress parameters/constants,

☐ No proper protocols on how to use or evaluate them,

IID. FINAL SUMMARY QUESTIONS FOR GEOTECHNICAL/MATERIALS ENGINEER

39. Overall, please rate your satisfaction (could be your pavement design group) with respect to the methods followed to determine the resilient properties of soils/unbound bases:

    Subgrade

    ☐ Not satisfied

    ☐ Satisfied, but methods could still be improved

    ☐ Well satisfied

    Unbound Base

    ☐ Not satisfied

    ☐ Satisfied, but methods could still be improved

    ☐ Well satisfied

40. If the answer is not satisfied or satisfied, but methods could still be improved, please cite the reasons for your responses.

    Subgrade

    ☐ Current methodology is too complicated

    ☐ Requires simple and practical standard laboratory test procedures

    ☐ Requires simple and practical standard field FWD and other test procedures

    ☐ Others,

    Unbound Base

    ☐ Current methodology is too complicated

    ☐ Requires simple and practical standard laboratory test procedures

    ☐ Requires simple and practical standard field FWD and other test procedures

    ☐ Others,

41. Please identify any other issues pertaining to resilient properties of subgrades/unbound bases that you feel should be addressed in this synthesis.

PART III: PAVEMENT DESIGN

1. When designing pavements, which method is used primarily?

    ☐ 1972 AASHTO Design Guide

    ☐ 1986 AASHTO Design Guide

    ☐ 1993 AASHTO Design Guide

    ☐ *Mechanistic Empirical Pavement Design Guide* (*MEPDG*)

    ☐ Agency-Specific Mechanistic Procedure

    ☐ Agency-Specific Empirical Procedure

    ☐ **If the responses are the last two, we would like to request you to e-mail/mail the two documents. Thanks in advance.**

2. What moduli property is considered true moduli for pavement design?

   Subgrade

   ☐ Resilient Modulus from Lab

   ☐ Resilient Modulus from Field FWD

   ☐ Other (please cite reference or provide a brief description):

   Unbound Base

   ☐ Resilient Modulus from Lab

   ☐ Resilient Modulus from Field FWD

   ☐ Other (please cite reference or provide a brief description):

3. Do you provide any input to Materials/Geotechnical engineers with regards to resilient modulus testing? If the answer is no, please skip this question. If the answer is yes, please provide the following details:

   ☐ Applied stresses in the lab:

   ☐ Moisture conditioning in the lab:

   ☐ Correction factor for Resilient Modulus from lab:

   ☐ Correction factor for Resilient Modulus from FWD:

4. If the stress analysis underneath a pavement shows negative (tensile) stresses either in the base or subgrade layer, what type of recommendations do you provide to Geotechnical/Materials engineer:

   ☐ No, we have not come across such problem

   ☐ Yes, but no recommendations were made

   ☐ Yes, the following recommendations are used. Please list them here:

5. What, if any, computer programs are used by your agency for design of pavements?

   ☐ DARWIN

   ☐ *MEPDG*

   ☐ Others (list the name of program):

6. For determining the effective roadbed resilient modulus, how do you consider seasonal variations?

   ☐ By using laboratory tests on samples at different moisture content conditions

   ☐ By performing field FWD tests on subgrades at different moisture states

   ☐ Other (please cite reference or provide a brief description):

7. For characterizing the structural coefficients of unbound base, which procedures do you follow?

   ☐ Not sure, we use the pavement design software

   ☐ 1993 AASHTO Design Guide

   ☐ Other (please cite reference or provide a brief description):

   ☐ Locally developed correlation (please provide a brief description):

8. For characterizing the structural support of subgrades (either in the form of a SN or others), which procedures do you follow?

   ☐ Not sure, we use the pavement design software

☐ 1993 AASHTO Design Guide

☐ Other (please cite reference or provide a brief description):

☐ Locally developed correlation (please provide a brief description):

9. Overall, please rate your satisfaction (response should be in terms of design group, not in terms of an individual) with respect to the use of resilient properties of soils used in the pavement design:

Subgrade

☐ Not satisfied

☐ Satisfied, but could still be improved

☐ Well satisfied

Unbound Base

☐ Not satisfied at all

☐ Satisfied, but could be improved

☐ Well satisfied

10. If the answer is not satisfied or satisfied but could be improved, please mark the reasons for your responses. Also, please rank the top three of your choices.

Subgrade

☐ Design methodology is too complicated,

☐ Require simple and practical standard laboratory test procedures,

☐ Require simple and practical standard field FWD and other test procedures,

☐ Require better correlations,

☐ Should consider using LTPP data,

☐ Others,

Unbound Base

☐ Design methodology is too complicated,

☐ Require simple and practical standard laboratory test procedures,

☐ Require simple and practical standard field FWD and other test procedures,

☐ Require better correlations,

☐ Should consider using LTPP data,

☐ Others,

11. Please identify any other issues pertaining to resilient properties of subgrades/unbound bases that you feel should be addressed in this synthesis.

THANK YOU VERY MUCH FOR YOUR HELP AND COOPERATION

Please return the completed questionnaire by January 31, 2007, to Dr. Anand Puppala.

APPENDIX B

SURVEY RESPONDENT INFORMATION

GEOTECH SURVEY RESPONDENTS

Agency	Division	Name
Alabama DOT	Materials and Tests	Becky Keith
Arizona DOT		Douglas Alexander
Arkansas State Hwy. & Trans. Dept.	Materials Division— Geotechnical Section	Jonathan Annable
California DOT (Caltrans)	Geotech	Imad Basheer
Colorado DOT	Materials	Cheng K. Su
Connecticut DOT	Geotech	Leo Fontaine
Washington DC DOT/IPMA	Material/Pavement Management	Lawrence Chung
Delaware DOT	Materials	Jim Pappas
Georgia		J. T. Rabun
Hawaii DOT	Geotechnical Unit	Brandon Hee
Idaho Transportation Dept.	Materials	Tri Buu
Illinois Dept. of Transportation	Bureau of Materials/Soils Lab	Riyad Wahab
Indiana	Geotech	Daehyeon Kim
Kansas Department of Transportation	Geotechnical Unit	Greg Schieber
Louisiana DOTD	Pavement and Geotechnical Design	Jeffrey R. Lambert
Maine Department of Transportation	Planning	Stephen Colson
Maryland State Highway	Soils & Aggregates and Field Exploration	Jeffrey Withee
Massachusetts Highway Department	Pavement Management	Edmund Naras
Minnesota DOT	Research Division	Shongtao Dai
Mississippi DOT	Consultant	William F. Barstis
Missouri DOT	Construction and Materials	John Donahue
Montana	Geotech	Dan Hill
North Dakota	Materials and Research Division	Josey Milbradt
Nebraska Dept. of Roads	Materials and Research Division	Omar Qudus and Mick Syslo
Nevada DOT	Materials Division	Dean Weitzel
New Hampshire DOT	Pavement Management Section	Charles Dusseault
New Mexico DOT	Materials	Bob Meyers
North Carolina DOT	Geotechnical	Njoroge Wainaina
New York DOT	Technical Services Division	M. Makbul Hossain
Ohio DOT	Geotech	Gene Geiger
Pennsylvania DOT	Materials and testing	Kerry Petrasic
South Dakota DOT	N/A	Kevin Griese
South Carolina DOT		G. Michael Lockman
Tennessee	Geotechnical Section	Len Oliver
Texas	Branch Manager, Geotech	Mike Murphy
Utah Department of Transportation	Materials Division	Timothy D. Biel
Vermont Agency of Transportation	Material and Research	Christopher C. Benda
Virginia DOT	Materials Division	Stanley L. Hite
Wisconsin	Materials	Linda Pierce
Wyoming DOT	Materials	Ms. Jamie Sharp

PAVEMENT SURVEY RESPONDENTS

Agency	Division	Name of Contact
Alabama DOT	Bureau of Materials and Tests	Gary M. Brunson
Alaska DOT&PF	Materials	Scott Gartin
Arizona DOT	Intermodal Transportation Division	Paul Burch
Arkansas Hwy. & Trans. Dept.	Roadway Design Division	Phil McConnell
California DOT (Caltrans)	District materials engineers	Imad Basheer
Colorado Dept. Of Transportation	Pavement Design Program	Jay Goldbaum
Washington DC DDOT/QA/QC Division	IPMA	Lawrence Chung
Delaware DOT	Materials & Research	Jim Pappas
Florida DOT	Design	Bruce Dietrich
Georgia DOT	Office of Materials and Research	JT Rabun
Hawaii DOT	Geotechnical and Pavement Design Section	Herbert Chu
Illinois DOT	Bureau of Materials & Physical Research	Amy Schutzbach
Indiana DOT	Planning	Kumar P. Dave
Kansas DOT	Pavement Design	Greg Schieber
Kentucky	N/A	Paul Looney
Louisiana DOTD	Pavement & Geotechnical Design	Jeffrey R. Lambert
Maine DOT	Highway Design	Karen Gross
Massachusetts	N/A	Kevin Fitzgerald
Michigan Dept. Of Transportation	Varies depending on the project	Michael Eacker
Minnesota DOT	Pavement Design	Bruce Chadbourn
Mississippi DOT	Roadway Design	William F. Barstis
Montana DOT	Surfacing Design Unit	Daniel Hill
North Carolina DOT	Pavement Management Unit	Judith Corley-Lay
North Dakota DOT	Materials & Research	Tom Bold
Nevada DOT	Roadbed Design	Michele Maher
New Mexico	N/A	Joe Sanchez
New Hampshire DOT	Materials & Research	Eric Thibodeau
New York State DOT	Design Division	M. Makbul Hossain
Ohio DOT	Office of Pavement Engineering	Roger Green
Oklahoma Dept. Of Transportation	Roadway Design	Jeff Dean
Pennsylvania DOT	N/A	Don Dawood
Puerto Rico	Pavement Management Office	Wilfredo Castro-Hernandez
South Carolina DOT	Materials and Research	Andrew Johnson
South Dakota DOT	Materials & Surfacing	Gill L. Hedman
Texas Department of Transportation	Materials and Pavements	Joe Leidy
Utah Dept. of Transportation	Materials	Tim Biel
Vermont	N/A	Mike Pologurto
Virginia		Affan Habib
Washington State DOT	State Materials Laboratory—Pavements	Linda M. Pierce
Wisconsin DOT	Division of Trans. System Development	Laura L. Fenley

Note: N/A = not available

APPENDIX C

SUMMARY OF SURVEY RESULTS

GEOTECHNICAL/MATERIALS SURVEY RESULTS

The survey was transmitted to 50 state departments of transportation (DOTs), out of which a total of 41 responses were received. Salient details from these surveys are listed in the following:

Q1. *In how many pavement design projects per year (average) are resilient moduli properties of subgrades and unbound bases determined/measured?*

Twenty-two of the respondents reported that they do use resilient modulus tests in routine pavement design and 19 of them noted that they do not measure the resilient moduli properties of subgrades and unbound bases. The responses from state DOTs are presented in Figure 3 (see chapter two). Among the 22 respondents, half (11) stated that they perform resilient modulus tests in more than 20 pavement projects per year. Table C1 provides further details of these responses, in particular those who noted that they do not use resilient modulus tests.

TABLE C1
REASONS PROVIDED BY STATE DOTS FOR NOT PERFORMING TESTS FOR RESILIENT MODULI

Agency	Comment
Arizona	ADOT uses *R* values only in pavement design
Arkansas	Test performed on subgrade soils only
California	For routine designs, no testing is done for resilient modulus
Colorado	Test for *R* value and correlate to M_R
Illinois	Mostly on nonstate, or local, routes
Indiana	For all projects, M_R values are required
Massachusetts	High classification roadways only
Minnesota	Current pavement design does not use M_R
Mississippi	Consultant is developing a materials library of M_R values
Missouri	Nearly all use soil correlations
Nevada	NDOT measures *R* value to estimate resilient moduli
New Hampshire	Use of resilient modulus is being reviewed at this time
New Mexico	1993 AASHTO *R* value correlation
North Carolina	We have run tests for 20 years but do not have confidence
South Dakota	Estimated based upon liquid limit and CBR
Utah	We convert everything from a CBR value
Wisconsin	Primarily through FWD testing and back calculation

Q2. *Please indicate the types of soil that your agency has dealt with.*

The different types of soils and unbounded bases that respondents dealt with are presented in Figure 4 (see chapter two). The respondents were asked to choose more than one type of soil/unbound base materials, and hence the total number of responses exceeds 41. The majority of state DOTs (28 of 41 respondents) mentioned that they encounter or use silty clay soils, and 22 respondents reported that they use crushed stone aggregates in pavement layer systems. A few other responses about different subgrades/bases are given in Table C2.

TABLE C2
OTHER SOIL/UNBOUND BASE TYPES MENTIONED BY STATE DOTS IN THE SURVEYS

Agency	Comment	
	Subgrade Soil Types	Unbound Base Types
Delaware		Hot-mix millings
Maine	Peat	
Maryland	Chemically stabilized soils	
Montana	Pulverized RAP/gravel	
New Hampshire		Reclaimed asphalt/gravel
Pennsylvania	Silts (ML)	
South Dakota		Quartzite
Washington, DC	Uncontrolled fill	

Q3. *Does your agency use* ***laboratory methods*** *for the determination of resilient moduli properties? (Check all that apply.)*

Twelve respondents noted that they *do* use laboratory methods for the determination of resilient moduli properties.

Q4. *Who is responsible for performing resilient modulus (to be used for pavement design practice) laboratory tests?*

Among those who responded positively, eight respondents noted that geotechnical/materials laboratories are the responsible organization for performing resilient modulus tests. Three respondents noted that they use outside laboratories for these tests. Another six respondents chose other methods, which are summarized in Table C3.

TABLE C3
RESPONSES ON PARTIES THAT PERFORM RESILIENT MODULUS TESTS FOR STATE DOTS

Agency	Comment
Illinois	Field Falling Weight Deflectometer (FWD)
Indiana	In-house research lab plus outside INDOT
Maine	University (WPI) testing on 6 soil types
Minnesota	Research office
New York	Highway Data Services Bureau
Washington, DC	Geotechnical consultants

Q5. *Do you follow specific guidelines regarding the number of tests to be performed per volume of the subgrade/unbound base or length of the highway?*

Seven and three respondents follow specific guidelines regarding the number of tests to be performed per volume of the subgrade and unbound bases or length of the highway, respectively. Details of the guidelines for subgrades included one test per mile of roadway, one test per project per new pavement, two to six projects per year, and tests on soil samples when the soils vary.

Q6. *What laboratory method is typically used?*

Nine respondents reported that they use repeated load triaxial test to measure resilient moduli of soil samples. Five respondents noted that they use correlations with California Bearing Ratio (CBR) and *R* values. The AASHTO T-307 guide was followed by four state DOT respondents for determining the resilient modulus properties.

Q7. What procedure is followed in performing laboratory repeated load triaxial tests?

One respondent mentioned AASHTO T-294, four respondents noted AASHTO T-307, one follows TP-46 procedure, another two follow the NCHRP 1-28 A harmonized procedure, and one respondent follows modified resilient modulus test methods.

Q8. Provide more details about the test procedure followed by your agency.

No specific details are given by the respondents, and those who responded noted that they follow the test procedure according to the standard method.

Q9. Provide details on the laboratory specimens used in the resilient moduli tests. (Check all that apply.)

Eight and four state DOT respondents use laboratory-fabricated specimens for new and rehabilitated pavement design, respectively. Please see Figure 5 in chapter two for these details.

Q10. Describe the laboratory procedures followed for specimen preparation. (Check all that apply.)

Among the respondents, they follow impact compaction (four), static compaction (three), and vibratory compaction methods (two) to prepare laboratory specimens for M_R testing. Please see Figure 6 in chapter two for more details.

Q11. Is any moisture conditioning of specimens performed prior to resilient modulus testing?

Four respondents noted that they consider moisture conditioning of specimens before resilient modulus testing. No moisture conditioning is mentioned in the standard test procedures for resilient properties.

Q12. How many laboratory tests are performed for each subgrade and base location to establish average moduli properties?

Two respondents noted that they perform three tests for subgrade. Other agencies reported that the number of tests varies and depends on their engineering judgment. Arkansas State Highway and Transportation Department typically uses one test per one mile of roadway.

Q13. Which regression model form is used to analyze the laboratory resilient moduli results?

Among those that responded, Washington State uses a theta model ($M_R = k_1 \times \theta^{k2}$), Kansas DOT uses a deviatoric stress model ($M_R = k_3 \times \sigma_d{}^{k4}$), and Maryland State Highway Administration uses a three-parameter regression model ($M_R = k_1 \times (Sc)^{k2} \times (S3)^{k3}$).

Q14. How do you determine the field resilient moduli (for pavement design) from the laboratory test results?

Only one respondent noted using a regression model with field-confining and deviatoric stresses to determine resilient moduli. Another respondent applied field-confining and deviatoric stresses in the laboratory. Other responses are presented in Table C4.

TABLE C4
DETAILS OF OTHER METHODS TO DETERMINE FIELD RESILIENT MODULI FROM LABORATORY TEST RESULTS

Agency	Comment
Arkansas	Design Value is lowest M_R lab value.
Indiana	With representative confining stress and deviator stress
Maryland	Apply 85th percentile of saturated results (on the low end)

Q15. What are the problems of the laboratory resilient modulus tests? (Check all that apply and rate the top three of them by indicating 1, 2, and 3 in the comment box.)

The majority of state DOTs (6 of 41) responded that they are unsure whether this method provides true modulus of subgrade in the field. The overall responses for this question are presented in Figure 7 in chapter two.

Q16. What are the strong points of the laboratory resilient modulus tests?

Four respondents indicated that the laboratory resilient modulus tests are better test methods, and two respondents reported that these tests are a better indicator of field performance.

*Q17. Does your agency use **field methods** for the determination of resilient moduli properties? (Check all that apply.)*

Sixteen of 41 respondents stated that their agency performs field tests to determine the resilient moduli properties of soils.

Q18. Check the methods used by your agency to determine the field subgrade and unbound base moduli. (Check all that apply.)

Twenty-four respondents noted that they use Falling Weight Deflectometer (FWD) tests to determine resilient modulus of subgrade/unbound bases; three respondents use Dynaflect method; and one respondent uses GeoGauge methods. The respondent from Maine noted using the pavement seismic pavement analyzer (PSPA) method for research projects.

Q19. Explain the main intent in performing field FWD tests.

Twenty state DOTs noted that the main intent in performing field FWD tests is to determine subgrade moduli for pavement rehabilitation. Twelve state agencies indicated that FWD tests are useful in the determination of structural coefficients of pavement layers. Only three respondents reported that the FWD test is conducted to ensure that laboratory moduli represent field moduli.

Q20. Do you follow any specific guidelines regarding the number of FWD tests to be performed per length of the highway?

Eleven state DOTs responded that they follow specific guidelines regarding the number of FWD tests. Some respondents provided details, and these are presented in Table C5.

TABLE C5
SPECIFIC GUIDELINES FOLLOWED BY STATE DOTS REGARDING THE NUMBER OF FWD TESTS

Agency	Comment
Indiana	1993 AASHTO, ELMOD 5.0 software
Kansas	ASTM D4695
Maryland	Typically multiple weight drops at ~ 9000 lb MDSHA 2006 Pavement Design Guide
Massachusetts	Project and condition dependent
Mississippi	200-ft test interval
Missouri	Performed more for research
Montana	Network Level-250m, Project-100m
New York	Mostly follow LTPP Guide.
North Dakota	Urban every 50'; Rural every 200'
Ohio DOT	ODOT Pavement Design and Rehabilitation Manual
Washington	See e-mail

Q21a. Please provide the following information related to FWD tests and analysis.

The information provided by state DOTs relating to FWD tests (manufacturer of FWD) and analysis (interpretation of results) are summarized in Table C6.

TABLE C6
DETAILS OF FWD TESTS AND ANALYSIS

	Comments		
Agency	Backcalculation software	Responsible division for performing FWD tests	Responsible personnel/division for analyzing FWD tests
Colorado	—	Materials	Region pavement designer
DC	—	Consultant	Consultant
Illinois	Illi-Pave	Pavement Tech Unit	Same as above
Kansas	In-house spreadsheets	Pavement Evaluation	Pavement Design
Maine	DARWin 3.1	Planning	Planning
Maryland	Deflexus	Field Explorations Division	Pavement & Geotechnical Division
Massachusetts	Proprietary or AASHTO	Pavement	Pavement
Mississippi	ELMOD	Research Division	MS DOT Research Division
Missouri	Evercalc	Construction and Materials	Construction and Materials
Montana	Modulus	Materials/Pavement	Materials/Pavement Analysis/NDT Testing
Nevada	Modulus	Materials	Materials
New Mexico	Jils	Materials	Pavements
North Dakota	ELMOD	Materials and Research	Materials and Research Division
New York	DELMAT— NYSDOT Procedure	Pavement Management Section	Pavement Management Section
Ohio	In-house program	Pavement Engineering	Pavement Engineering
Washington	WSDOT EVERCALC	Pavements division	Pavement division
Wyoming	In-house program based on 1993 Guide	Field Services/Materials	Pavement Design Engineer/ Materials

Q21b. Please check mark the following that can be described as limitations of FWD methods. (Check all that apply and rate the top three of them by indicating 1, 2, and 3 in the comment box next to each response.)

Please see Figures 8 and 9 (in chapter two) for the responses on the limitations of FWD methods for both subgrade and unbound bases by responding state DOTs.

Q22. What are the strong points of the FWD tests? (Check all that apply.)

The majority of respondents (18 of 41) noted that the FWD tests are faster test methods. Fourteen respondents indicated this method as inexpensive (see Figure 10 in chapter two). Again, the respondents are asked to select more than one choice. As a result, the total number of the responses will exceed 41. Maryland State Highway Administration stated that this test can be performed in many test locations (150 per project). Ohio DOT pointed out the repeatability of these test results. Montana DOT states that this method would be good when used in conjunction with ground-penetrating radar (GPR).

Q23. Do you recommend the use of your FWD backcalculation software for other DOTs for pavement layer moduli determination?

Fourteen respondents agreed to share their FWD backcalculation software with other DOTs.

Q24. In your agency, are there any specific guidelines on how to interpret the FWD moduli? If the answer is yes, please provide the reference details and how we can get that information.

The information from a few state DOTs is summarized in Table C7.

TABLE C7
SPECIFIC GUIDELINES FOR INTERPRETING FWD MODULI

Agency	Comment
Colorado	Yes—use DARWIN
Indiana	1993 AASHTO Guide
Maryland	MDSHA 2006 Pavement Design Guide
New Mexico	*R*-value shift relative to lab results
New York	Yes. The method is under review

Questions Related to Other Nondestructive Tests (Dynaflect/seismic methods/GeoGauge/others):

Q25. Explain the main intent in performing these tests.

Only one respondent indicated using other nondestructive tests for quality control/quality assessment (QC/QA) studies and for indirect compaction quality evaluation for new pavement construction. Another respondent noted that they use these tests for the determination of subgrade moduli for pavement rehabilitation. Two respondents stated that they perform these tests to determine the structural coefficients of pavement layers.

Q26. Do you follow specific guidelines regarding the number of tests to be performed per volume of the subgrade/unbound base or length of the highway?

One respondent mentioned that they follow specific guidelines regarding the number of tests to be performed. The respondent from North Dakota reported that they perform these tests at 50-ft intervals in urban areas and in 200-ft intervals in rural areas.

Q27. Do you recommend this method for other DOTs for determination of layer moduli?

Out of three responses received for this question, one respondent agreed to recommend this method for other DOTs, and two respondents did not agree to recommend this method for other DOTs.

Q28. Please check mark the following that can be described as limitations of these methods. (Check all that apply and rate the top three of them by indicating 1, 2, and 3.)

The limitations identified by respondents for subgrades and unbound bases are presented in Figures C1*a* and C1*b*, respectively. The majority of state DOTs that responded opined that their major limitation would be the requirement of skilled personnel to analyze the test results. Respondents from Ohio mentioned that both nonlinearity of soil modulus and load magnitude applied in the test as limitations of these methods.

Q29. What are the strong points of these nondestructive tests? (Check all that apply.)

According to four respondents, nondestructive tests are observed to be faster test methods. Two respondents noted that these methods are inexpensive, while another two noted that these methods provide results that are not affected by boundary conditions. Another two respondents reveal that these methods provide reliable structural numbers for pavement design.

Q30. Overall, how do you assess the nondestructive field tests for moduli determination?

Three respondents noted that these test procedures are well established, whereas another three respondents pointed out poor reproducibility problems and the need for research on analysis routines.

FIGURE C1. Limitations of other nondestructive tests responses by state DOTs.

Q31. Does your agency use empirical or semiempirical correlations for the determination of resilient moduli properties?

Fourteen respondents stated that they use empirical or semiempirical correlations.

Q32. What types of correlations are used to determine the resilient moduli?

Direct correlations between resilient modulus and other soil properties are used for both subgrades and unbound bases by eight and six respondents, respectively (see Figure 11 in chapter two). Other correlations used by different DOTs are presented in Tables C8*a* and C8*b*.

TABLE C8
OTHER CORRELATIONS USED FOR DETERMINING RESILIENT MODULI BY STATE DOTS

(a) Subgrades

Agency	Correlation Type
Colorado	*R*-value correlate to M_R
Montana	MDT uses *R*-Value testing
Nevada	$M_R = f(R\text{-Value})$
New Mexico	$M_R = 1{,}000 + (555)(R\text{-value})$
North Dakota	FWD
Pennsylvania	CBR correlations
Utah	CBR Testing is used

(b) Unbound Bases

Agency	Correlation Type
Colorado	*R*-value correlate to M_R
Louisiana	Not at this time
Montana	MDT uses *R*-Value testing
New Mexico	$M_R = 1{,}000 + (555)(\text{R-value})$
North Dakota	FWD
Ohio	Estimated from research results

Q33. How were these correlations developed? Please provide additional details including the reference details, if available.

State DOTs (seven responded) reported that they use correlations recommended by the AASHTO design guide, and six state DOTs developed their own correlations locally using the database collected over several years. Only two respondents use the correlations drawn from the literature. Additional information provided by different agencies related to these correlations is summarized in Table C9.

TABLE C9
ADDITIONAL INFORMATION RELATED TO EMPIRICAL CORRELATIONS

Agency	Not local, from the papers published in the literature	Not local, from the recommended AASHTO design guide	Local, developed by the database collected over several years
Colorado		1972 AASHTO Guide	
Indiana		1993 AASHTO Guide	
Kansas			Yes, correlation with KS Triaxial Method
Louisiana			Correlations between Soil Support Value and MR
Massachusetts		1993 Guide and MEPDG	
Mississippi			Materials Library
Missouri		MEPDG	
Montana	NCHRP No.128		
Nevada			In house $M_R - R$ correlations
New Mexico		1993 AASHTO Guide	
New York	NYSDOT & CORNELL		
Utah		Combination of ’93 guide and MEPDG	

Q34. How do you characterize the level of reliability of the correlations used by your DOT?

The level of reliability of the correlations by state DOTs can be found in Figure 12 (in chapter two). The majority of agencies characterized the level of reliability of these correlations as fair for both subgrades (seven) and unbound bases (eight). Few agencies noted these methods as very good to good.

Q35. Do you check the correlation predictions by performing additional tests (laboratory or field nondestructive tests). If the answer is yes, please list type(s) of tests conducted.

Additional tests for evaluation are performed by five respondents for subgrades and by three respondents for unbound bases. Kansas stated that they verify the correlation predictions if they have field FWD data. Colorado specified that they perform plasticity index, gradation, density, and moisture tests to cross-check the correlation predictions.

Q36. Are the local correlations updated frequently? If the answer is yes, please specify the frequency time period for the updates?

Only one respondent noted updating their local correlations. The majority of respondents (13 respondents for subgrade and nine respondents for unbound bases) stated that they do not update their correlations.

Q37. Overall, please check mark the following that can be described as limitations of these methods. (Check all that apply and rate the top three of them by indicating 1, 2, and 3):

Figures 13*a* and 13*b* of chapter two present the limitations as identified by the DOT for subgrades and bases, respectively. The majority of state DOTs opined that the correlations were developed from a limited database.

Final Summary Questions for Geotechnical/Materials Engineer

Q38. Overall, please rate your satisfaction (could be your pavement design group) with respect to the methods followed to determine resilient properties of soils/unbound bases:

Twelve and 10 respondents are satisfied with the existing methods to determine resilient moduli properties of subgrades and unbound bases, respectively (see Figure 14 in Chapter 2). They also noted that these methods could still be improved.

Q39. If the answer is not satisfied or satisfied but methods could still be improved, please cite the reasons for your responses.

Figure 15 in chapter two presents a summary of various levels of satisfaction for the methods used for determining M_R. Table C10 lists a few of the reasons for unsatisfactory responses.

TABLE C10
OTHER REASONS FOR NO SATISFACTION IN CURRENT METHODS

Agency	Comments
Kansas	Correlation between lab and FWD
Minnesota	Data quality check procedures
New Mexico	Empirical
South Dakota	Interested in looking at new technology

Q40. Please identify any other issues pertaining to resilient properties of subgrades/unbound bases that you feel should be addressed in this synthesis.

Table C11 presents a few of the issues pertaining to resilient modulus of subgrades/unbound bases expressed by the state DOTs.

TABLE C11
OTHER ISSUES PERTAINING TO RESILIENT MODULUS OF SUBGRADE/UNBOUND BASES

Agency	Comments
Arkansas	Procedures should be developed to determine a recommended DESIGN M_R Value from the laboratory test results.
California	We do not test for M_R for routine designs and that is why most questions were left unanswered.
Colorado	FWD obtains M_R values for each drop; M_R values as input to rigid pavement design & do away with subgrade modulus *k*-value.
Connecticut	A research study was recently completed to address resilient properties. We are evaluating whether these range values/correlations need to be implemented.
Delaware	We have just started resilient testing.
Indiana	Most engineers do not care about the stress level. This should be pointed out in the synthesis study. Local data should be collected.
Maryland	A new pavement design methodology was recently introduced (MDSHA 2006 Pavement Design Guide).
Minnesota	1. How many LVDTs are needed to get accurate results; 2. Need to develop a set of data quality procedure to ensure high quality modulus; 3. How to relate lab M_R to the field M_R.
Missouri	Although we have not directly measured subgrade or unbound granular base resilient modulus with triaxial testing (T 307) for any previous projects, the U. of Missouri is in the midst of performing this test (at optimum and wet of optimum) on 30 subgrade soils and 5 granular base materials that are representative of Missouri sources. These results will be used to create a materials database library in the MEPDG for use in project designs.
Montana	MDT is considering using resilient modulus testing in the future. It is believed that the M_R testing will provide better inputs for the M-E Pavement Design Guide. The current *R*-Value testing program is outdated, but currently MDT is still using it because of our familiarity with it and a multitude of past data and experience.
North Carolina	Test repeatability has been our greatest concern. Cost of the test is also prohibitive for small projects.
Washington	We have no real issues with the FWD or backcalculation process; however, improvements are still needed to refine the procedure and to improve the accuracy and repeatability of the results.
Washington, DC	No specific issues at this time
Wyoming	The 1993 AASHTO Design Guide method predicts Pavement Modulus and Subgrade Modulus; however, there are never only two layers. Perhaps it is time for a new standard to be adopted. Also, the AASHTO T-307 procedure could use some attention. We have a test device used in a research capacity only and have found that the equipment specified in the procedure is very difficult to acquire; in fact, we have resorted to custom fabrication. Furthermore, detailed guidelines on interpreting the data and a precision and bias study would be helpful.

Pavement Group Survey Results

The survey was transmitted to 50 state DOTs, and a total 40 responses were received. Salient details from these survey analyses are presented in the following:

Q1. When designing pavements, which method is used primarily?

Most of the state DOTs (24 of the total DOTs contacted) mentioned that they use the 1993 AASHTO design guide to design pavements. This was followed by seven respondents who mentioned that they use 1972 design guide. A summary of the responses is presented in Figure 16 (in chapter two). Apart from the standard design guides, a few state agencies, including Illinois, Washington, New York, Alaska, and Texas, mentioned that they use agency-developed procedures. Only one agency reported using MEPDG.

Q2. What moduli property is considered true moduli for pavement design?

The majority of state DOTs use resilient modulus obtained from different methods other than direct laboratory and field measurement. Indirect methods using CBR values, grain size/soil classifications, and *R* value for subgrades have been used in correlations to estimate moduli of both subgrade and unbound bases. Figure 17 (in chapter two) shows the number of responding state DOTs that use different methods to determined resilient moduli for pavement design.

Table C12*a* and C12*b* provide further details of the soil properties through which the moduli of subgrades and bases are determined.

TABLE C12
MODULI DETERMINATION PROCEDURES FOLLOWED BY THE DOTS

(a) Subgrade

State DOT Agency	Properties to Estimate M_R
California (Caltrans)	*R*-value
Georgia	Soil Support is correlated to soaked CBR
Hawaii	*R*-value
Illinois	Grain size analysis.
Maine	Correlated by soil classification/soils
Minnesota	*R*-value
Nevada	*R*-value
New Hampshire	Soil Support value
Ohio	CBR
Pennsylvania	CBR
Puerto Rico	Soil classification
South Carolina	Laboratory CBR
South Dakota	Liquid Limit & CBR
Virginia	CBR values

(b) Unbound Bases

Agency	Comment
Alabama	Assigned a layer coefficient
California (Caltrans)	*R*-value and gravel factor for base
Delaware	Default
Florida	Standard values for approved base types
Georgia	Structural Coefficient
Hawaii	*R*-value
Illinois	Historical typical values from the design manual
Minnesota	Granular Equivalent (GE)
Montana	We assume the base modulus is 30,000
Nevada	*R*-value
New Hampshire	Soil Support value
Ohio	Default value
Puerto Rico	Soil class correlations with Mr
South Carolina	Structural coefficients
South Dakota	Typical values from the 1993 Guide
Virginia	From CBR values

Q3. Do you provide any input to Materials/Geotechnical engineers with regards to resilient modulus testing? If the answer is no, please skip this question. If the answer is yes, please provide the following details:

The majority of respondents (33 of 41) noted that they do not provide any input to Materials/Geotechnical engineers with regard to resilient modulus property. Other respondents (11) noted that they provide input in various forms, which can be seen in Figure 18 (in chapter two). The total responses exceed 41 because respondents can choose more than one answer for their response. Table 2 (in chapter two) summarizes more details about the responses of the interactions between Pavement engineers and Geotechnical engineers.

Q4. If the stress analysis underneath a pavement shows negative (tensile) stresses either in the base or subgrade layer, what type of recommendations do you provide to Geotechnical/Materials engineer?

Four respondents are aware of having negative (tensile) stresses either in the base or subgrade layers. The few DOTs that responded noted that they either consider geosynthetics or use thicker pavements.

Q5. What, if any, computer programs are used by your agency for design of pavements?

Figure 19 (in chapter two) shows the number of respondents that use computer methods to design pavements. Twenty of the 40 responding state DOTs noted that they follow the DARWIN program to design pavements. Another 16 use other methods, such as spreadsheets and other guides, whose details are presented in Table 3 (in chapter two).

Q6. For determining the effective roadbed resilient modulus, how do you consider seasonal variations?

Figure 20 (in chapter two) depicts the total number of respondents who consider seasonal variations in determining the resilient modulus. For determining the effective roadbed resilient modulus, three respondents use laboratory tests, four use field FWD tests, and 15 use other methods, which are summarized in Table 4 (chapter two).

Q7. For characterizing the structural coefficients of unbound base, which procedures do you follow? and

Q8. For characterizing the structural support of subgrades (either in the form of a SN or others), which procedures do you follow?

The percentage of respondents for both bases and subgrades are shown in Figure 21 (see chapter two). The majority of state DOTs (17 respondents) use local correlations; six DOTs use the 1993 AASHTO design guide for determining structural coefficients. Tables C13 and C14 summarize the written responses received from state DOTs with respect to characterization of structural coefficients of unbound bases and subgrades, respectively.

TABLE C13
RESPONSES ON CHARACTERIZATION OF STRUCTURAL COEFFICIENTS OF UNBOUND BASES

Agency	Response
Alabama	Coefficients were established soon after AASHO Road Test and have not been varied. They were based on CBR and material characteristics.
Alaska	Reduction Factors are applied.
California (Caltrans)	We use known gravel factor for bases (like layer coefficient in AASHTO). This is a limitation of course because it restrict us from using new materials. Only traditional materials that we know their gravel factors are used.
Colorado	CDOT has a list of coefficients based on *R*-Value.
Florida	Use standard base material type values that were developed through lab tests, plate load pit tests, and then field test sections to develop structural coefficients.
Georgia	Historically established structural coefficients
Illinois	Do not use structural coefficients
Indiana	For unbound base, we use layer coefficient as 0.14.
Maine	AASHTO 1993
Michigan	We use the structural coefficients recommended by the AASHO Road Test.
Minnesota	Granular Equivalent chart
Mississippi	Use a value of 0.09
Montana	We give new unbound base a SC of 0.14 per in. We reduce the SC of existing base using the gradation (i.e., P200) and adjust the SC based on the infiltration of fines.
Nevada	1993 AASHTO
New Hampshire	Layer coefficients were determined by research.
New York	We use NYSDOT Thickness Table for both PCC and HMA pavement.
North Carolina	Unbound base coefficient is 0.13
North Dakota	Selected from range given in 1993 AASHTO Design Guide.
Ohio	Unbound base is assigned a structural coefficient of 0.14.
Pennsylvania	Structural coefficients of unbound bases are set for all dense bases and open graded bases.
Puerto Rico	1993 AASHTO Design Guide
South Carolina	Our structural coefficients were developed in the late 1960s based on full-scale static deflection testing of test pavements compared to reference pavements constructed with AASHO Road Test material.
South Dakota	Suggested values from the 1993 guide
Texas	Backcalculation of in situ modulus using deflection data.
Utah	Defaults in 1993 guide
Vermont	We have several FWD test results for pavement materials. If we try something new, we attempt to estimate it using our collective engineering judgment.
Washington	For rehabilitation—backcalculation for determining in-situ stiffness & LF; For new design—established values based on experience.

TABLE C14
RESPONSES ON CHARACTERIZATION OF STRUCTURAL COEFFICIENTS/NUMBERS OF SUBGRADES

Agency	Response
Alabama	AASHTO T 307-99, Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials
Alaska	FWD Stiffness Values
California (Caltrans)	We use the California test method for *R*-value.
Colorado	CDOT has a list of coefficients based on *R*-Value.
Florida	Lab M_R testing for new construction of existing alignment and potential borrow pits. FWD backcalculation of M_R for existing alignments.
Georgia	Soil Support is correlated to soaked CBR.
Indiana	CBR or Resilient modulus from lab test
Maine	AASHTO 1993
Michigan	We backcalculate a resilient modulus from FWD using the MICHBACK program or use testing done in the 1970s/1980s on typical soil types.
Minnesota	Granular Equivalent chart
Mississippi	Use double correlation:& LF; 1. Use soil classification to get soaked CBR&LF; 2. Use CBR to get soil support value for flexible and "*k*" value for rigid.
Montana	*R*-Value testing correlations for resilient modulus. We will use FWD modulus as a supplement to the *R*-Value modulus.
Nevada	1993 AASHTO
New Hampshire	Currently, we do not characterize subgrades on a project specific basis. We assume a Soil Support Value of 4.5 for all cases. Based on the types of soil that we have this is conservative but it's our current practice.
New York	NYSDOT procedure which was developed based on AASHTO 1993 Guide.
North Dakota	Selected from range given in 1993 AASHTO Design Guide
Ohio	Group index and atteberg limits are used to estimate CBR. CBR is used to estimate M_R.
Oklahoma	Resilient Modulus as determined by AASHTO T-307
Pennsylvania	CBR
PR A&TA	1993 AASHTO Design Guide
South Carolina	The design SSV is based on laboratory CBR testing of the predominant soil types expected on the project and adjusted by the Geotechnical Materials Engineer to account for the potential variability on a given project.
South Dakota	Suggested values from the 1993 guide
Texas	Backcalculation of in situ modulus using deflection data.
Utah	Defaults in 1993 guide
Vermont	Subgrade, SN = 0
Virginia	AASHTO

Q9. *Overall, please rate your satisfaction (response should be in terms of design group, not in terms of an individual) with respect to the use of resilient properties of soils used in the pavement design:*

Figure 22 (see chapter two) presents the number of responses for various satisfaction levels derived from the use of resilient properties in the pavement design. Half of the respondents are satisfied with the use of resilient properties of subgrades in designing pavements. Twelve respondents expressed satisfaction with respect to the use of resilient properties of bases for the pavement design.

Q10. *If the answer is not satisfied or satisfied but could be improved, please mark the reasons for your responses. Also, please rank the top three of your choices.*

The reasons for being not satisfied with using resilient modulus properties in pavement design are further explored. These responses are summarized in Figures 23 and 24 (in chapter two) for subgrades and bases, respectively. The majority of respondents attributed reasons for their dissatisfaction to the complicated laboratory or field test procedures and complicated correlations required to determine the moduli of both subgrades and unbound bases.

APPENDIX D

MODULI OF VARIOUS SOILS AND AGGREGATES

Recommended Moduli from Ohio Studies (from Masada et al. 2004)

Table 4.27: Recommended Properties for Flexible Pavements in Ohio

Layer/Material	M-E Property		Property Determination or Property Value
Asphalt Concrete (AC)	Dynamic Modulus |E*|		[Level 1] - Measure by ASTM D3496.
			[Level 2] - Estimate from Witczak equation (see Note 1) or from Eq. 1 (see Note 2).
			[Level 3] - Use the typical values found in literature (see Note 3 below).
	Resilient Modulus (M_R)		[Level 1] - Measure by SHRP P07 or ASTM D4123. Establish a correlation with the AC temp.
			[Level 2] - Use the formula of: M_R (million psi) = $0.0002T^2 - 0.0502T + 3.2371$ where T (°F) along with the regional AC temp. information (in Note 4).
			[Level 3] - (the same as Level 2).
	Poisson's Ratio (μ)		[Level 1] - Measure by SHRP 07 or ASTM D4123.
			[Level 2] - Use the formula of: $\mu = -0.00004T^2 + 0.012T - 0.2837$ where T (°F)
			[Level 3] – (the same as Level 2).
Base/Subbase	Resilient Modulus (M_R) (See Notes 6 & 7 below for the values of Poisson's ratio)	Unbound	[Level 1] - Measure by AASHTO T46.
			[Level 2] - Estimate from CBR or R value (see Note 5).
			[Level 3] - Use a typical value of 20 ksi.
		ATB	[Level 1] - Measure by SHRP 07 or ASTM D4123.
			[Level 2] - Use the formula of: M_R (million psi) = $0.00001T^2 - 0.0116T + 1.2627$ where T (°F); along with state-wide ATB temp. of 48 °F (spring, fall), 75 °F (summer), and 33 °F (winter).
			[Level 3] - (the same as Level 2).
		PATB	[Level 1] - Measure by SHRP 07 or ASTM D4123.
			[Level 2] - Use the formula of: M_R (million psi) = $0.00005T^2 - 0.0117T + 0.7481$ where T (°F); along with state-wide PATB temp. of 48 °F (spring, fall), 75 °F (summer), and 33 °F (winter).
			[Level 3] -(the same as Level 2).
		PCTB	[Level 1] - Measure by ASTM D3496 (at 75 °F).
			[Level 2] - Use a typical value of 0.75×10^6 psi.
			[Level 3] -(the same as Level 2).
		LCB	[Level 1] - Measure by ASTM D3496 (at 75 °F).
			[Level 2] - Use a typical value of 1.0 million psi.
			[Level 3] - (the same as Level 2).
Subgrade	Resilient Modulus (M_R)		[Level 1] - Measure by AASHTO T46.
			[Level 2] – Estimate from CBR or R value (see Note 8). Or, backcalculate from FWD test data, degree of saturation data, or q_u data (see Note 9).
			[Level 3] – Use a typical value for the soil type (see Note 10).

Information for Base and Subgrades are only given here.

5. According to AASHTO (1993): M_R (ksi) = 1.5(CBR)
ODOT recommend a slightly different correlation: M_R (ksi) = 1.2(CBR)

A better prediction model may be the one that takes into account of the effect of confining stress (σ_3) level:

M_R (ksi) = $6\theta^{0.4}$ where θ = bulk stress (psi) = $\sigma_d + 3\sigma_3$; and σ_d = deviatoric stress.

6. Poisson's ratio (μ) values of ATB & PATB are:

$\mu = 0.00004(T^2 + T) + 0.0345$ for ATB
where T = Temperature (°F)

The seasonal average temperatures of ATB & PATB are:

Region in Ohio	Average Temperature of ATB (°F) for:			
	Spring	Summer	Fall	Winter
North, Central, South	48	75	48	33

The above equation translates to seasonal average Poisson's ratio values listed in the table below (based on the seasonal average temperatures of AC reported by Figueroa, 2002).

Region in Ohio	Poisson's Ratio of ATB & PATB during:			
	Spring	Summer	Fall	Winter
North, Central, South	0.13	0.26	0.13	0.08

7. Poisson's ratio (μ) values for other materials are:

$\mu = 0.35$ for Unbound Granular Base (ex. DGAB)
$\mu = 0.15$ to 0.20 for Lean Concrete Base (LCB)
$\mu = 0.15$ to 0.20 for Permeable Cement-Treated Base (PCTB)
$\mu = 0.35$ for Subgrage Soils

8. M_R (psi) = 1,500(CBR) AASHTO Guide (1993)
M_R (psi) = 1,200(CBR) Formula used by ODOT
M_R (MPa) = 10.3(CBR) Formula used by Asphalt Institute
M_R (psi) = 1,000 + 555(R) AASHTO Guide (1993)

9. According to Figueroa (2002), resilient modulus of subgrade soil can be estimated by:

M_{Ri} (ksi) = [Log(δ) – A0 – A1*(t_{AC}) – A2*(t_B) – A3*($M_{R\text{-}AC}$)]/A4

where δ = FWD deflection at the plate (in.); t_{AC} = AC layer thickness (in.); t_B = Granular base layer thickness (in.); $M_{R\text{-}AC}$ = AC resilient modulus (ksi); and A0 through A4 = regression constants given by the table below.

Soil Type	Load P (kN)	A0	A1	A2	A3	A4
A-4	40.0 (9 kip)	-0.67328	-0.01775	-3.9954E(-4)	-4.6293E(-5)	-2.9088E(-3)
	53.4 (12 kip)	-0.55789	-0.01746	-4.9750E(-4)	-4.5820E(-5)	-2.9211E(-3)
	66.7 (15 kip)	-0.46776	-0.01726	-5.7782E(-4)	-4.5423E(-5)	-2.9271E(-3)
A-6	40.0 (9 kip)	-0.67834	-0.01761	-5.6275E(-4)	-4.5594E(-5)	-3.2383E(-3)
	53.4 (12 kip)	-0.56192	-0.01731	-6.6143E(-4)	-4.5079E(-5)	-3.2862E(-3)
	66.7 (15 kip)	-0.47122	-0.01711	-7.3800E(-4)	-4.4741E(-5)	-3.2981E(-3)
A-7	40.0 (9 kip)	-0.61095	-0.01719	-9.1448E(-4)	-4.3979E(-5)	-4.4855E(-3)
	53.4 (12 kip)	-0.49853	-0.01674	-1.1505E(-3)	-4.3822E(-5)	-4.4056E(-3)
	66.7 (15 kip)	-0.40663	-0.01670	-1.0849E(-3)	-4.3071E(-5)	-4.4847E(-3)

Also, according to Figueroa (1994),

M_{Ri} (ksi) = - 0.3289S + 37.908 for A-4 soils (relatively undisturbed)
M_{Ri} (ksi) = - 0.4135S + 43.290 for A-4 soils (disturbed - recompacted)
M_{Ri} (ksi) = - 0.1206S + 17.245 for A-6 soils (relatively undisturbed)
M_{Ri} (ksi) = - 0.2126S + 22.263 for A-6 soils (disturbed – recompacted)
M_{Ri} (ksi) = - 0.2549S + 28.010 for A-7 soils (relatively undisturbed)
M_{Ri} (ksi) = - 0.4031S + 41.137 for A-7 soils (disturbed - recompacted)

where S = degree of saturation (%).

$$S(\%) = \frac{w(\%)}{\left(\frac{\gamma_w}{\gamma_d}\right) - \left(\frac{1}{SG}\right)}$$

where γ_w = unit weight of water = 62.4 pcf; and γ_d = dry unit weight of soil (pcf).

According to University of Illinois (1979),

M_R (ksi) = 0.86 + 0.307(q_u) where q_u = unconfined compression strength (psi).

10. According to Masada & Sargand (2002),

M_R = 17 to 39 (ave. = 32) ksi for A-1 soils
M_R = 2 to 36 (ave. = 11) ksi for A-4 soils
M_R = 2 to 29 (ave. = 10) ksi for A-6 soils
M_R = 2 to 25 (ave. = 11) ksi for A-7-6 soils

Typical subgrade resilient modulus (M_R) values reported in literature (Huang, 1993):

Soil Type	Condition			
	Dry	Wet - No Freeze	Wet - Freeze	
			Unfrozen	Frozen
Clay	15 ksi	6 ksi	6 ksi	50 ksi
Silt	15 ksi	10 ksi	5 ksi	50 ksi
Silty or Clayey Sand	20 ksi	10 ksi	5 ksi	50 ksi
Sand	25 ksi	25 ksi	25 ksi	50 ksi
Silty or Clayey Gravel	40 ksi	30 ksi	20 ksi	50 ksi
Gravel	50 ksi	50 ksi	40 ksi	50 ksi

Malla and Joshi (2006)

- **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)

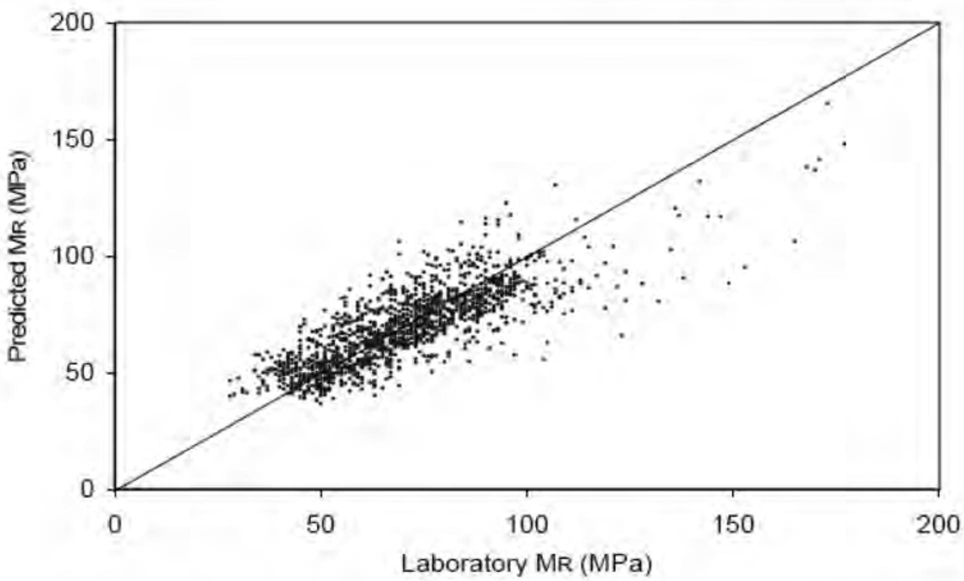


Figure 78. Predicted M_R vs. Laboratory M_R for all Coarse Grained soils

- **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).

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

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

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

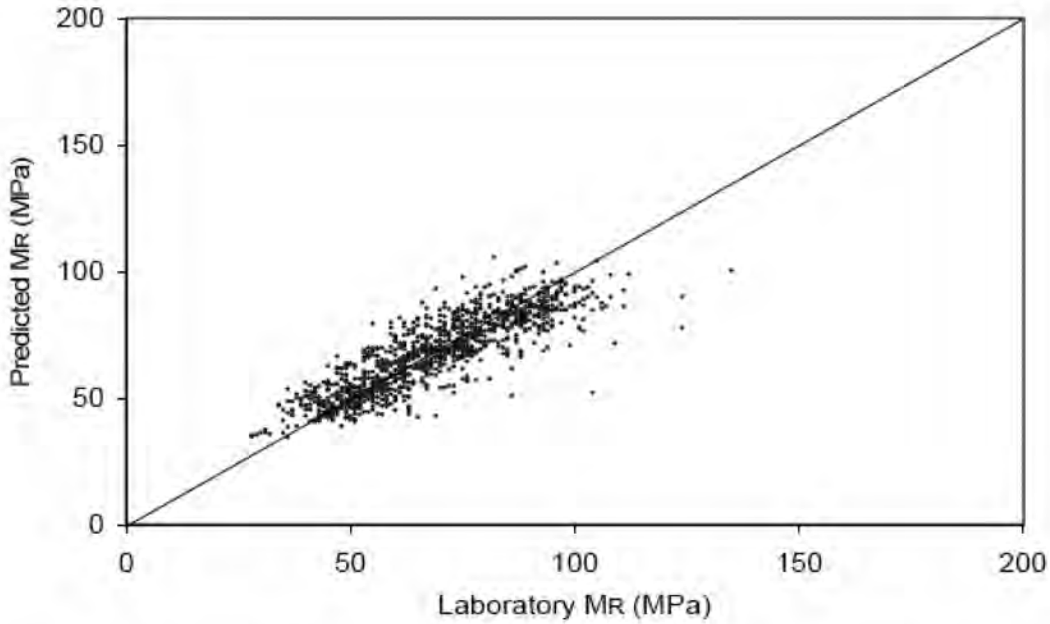


Figure 79. Predicted M_R vs. Laboratory M_R for Coarse Grained soils with CU≤100

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.

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

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

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

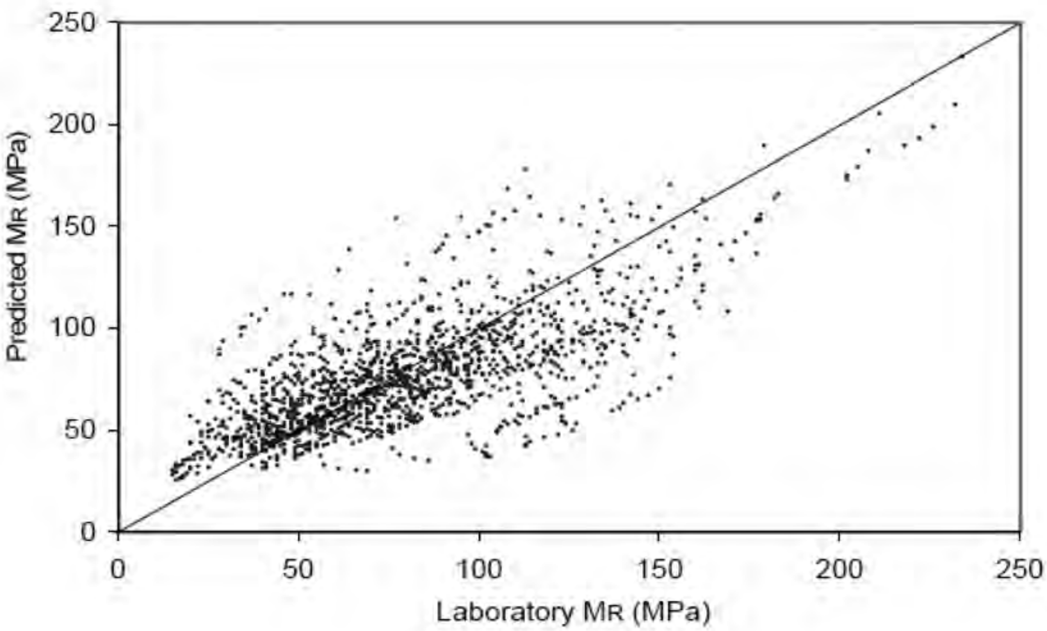


Figure 83. Predicted M_R vs. Laboratory M_R for Fine Grained soils

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation