Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate

DETAILS

17 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-30814-4 | DOI 10.17226/22211

AUTHORS

Soheil Nazarian

January 2015

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Responsible Senior Program Officer: Edward T. Harrigan

Research Results Digest 391

MODULUS-BASED CONSTRUCTION SPECIFICATION FOR COMPACTION OF EARTHWORK AND UNBOUND AGGREGATE

This digest summarizes key findings of research conducted in NCHRP Project 10-84, "Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate," by the University of Texas at El Paso, with the support of the University of Texas at Arlington and the Louisiana Transportation Research Center, Baton Rouge. The research was directed by the principal investigator, Dr. Soheil Nazarian, University of Texas at El Paso. This digest is based on the project final report authored by Drs. Soheil Nazarian, Mehran Mazari, and Imad Abdallah of the University of Texas at El Paso, Dr. Anand Puppala of the University of Texas at Arlington, and Drs. Louay Mohammad and Murad Abu-Farsakh of the Louisiana Transportation Research Center. The complete project final report and twelve appendices are available to download from the TRB website (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2908).

CONTENTS

INTRODUCTION

Earthwork and unbound aggregates, collectively called compacted geomaterials, are a significant portion of the construction of pavements. Much of the distress observed in pavements, particularly in flexible pavements, can be traced to problems in geomaterials. Good pavement performance can only be assured with (1) appropriate process control to ensure the geomaterials used are similar to the ones selected, (2) proper processing of the material to ensure that the material is uniformly mixed and contains an appropriate amount of moisture before compaction, and (3) adequate compaction equipment to ensure proper density and stiffness. Currently, the nuclear density gauge is the primary tool for quality management to ensure that appropriate density. Despite the importance of moisture content at the time of compaction to the quality of the final product, not all highway agencies include moisture content in their specifications. However, measurement of moisture content and dry density does not directly tie the construction quality to mechanistic-empirical (ME) design processes where stress and modulus are key input and output parameters. In-situ nondestructive testing (NDT) devices that estimate the stiffness parameters of a constructed pavement structure are now commonly available. Such stiffness parameters provide a direct link to the pavement performance predicted through a mechanistic-empirical based design process. Transformation from a density-based to a modulus-based quality assurance approach involves technical and organizational challenges that must be recognized and addressed in order to develop an efficient, practical modulus-based specification.

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

OBJECTIVE AND SCOPE

The objective of NCHRP Project 10-84 was to develop a modulus-based construction specification for acceptance of compacted geomaterials with the following features:

1. The specification should be based on field measurement of modulus and moisture content.
2. Acceptance criteria should be correlated with design moduli.
3. The specification should be compatible with a variety of compacted geomaterials.
4. The specification should consider the principles of unsaturated soil mechanics.
5. Available models and testing technologies should be incorporated in the specification.

Migration from traditional density-based specifications to a modulus-based approach should provide continuity among the design, construction, and laboratory testing wherever possible. Such an approach may ideally follow the flowchart in Figure 1, with due consideration to the several inter-related parameters briefly discussed below.

The requirements of structural design software should be considered from the beginning so that the level of sophistication of the pavement design, laboratory testing, and field testing are balanced. The construction specification should be ideally tied to a ME design algorithm. The response models in the ME algorithms can be as simple as axisymmetric linear-elastic layered models where a single modulus should be assigned to each layer or as complex as three-dimensional nonlinear finite-element models where the modulus is defined by two to five parameters. Depending on the level of sophistication of the analysis and budgetary constraints, design moduli can be estimated from either empirical relationships, or presumptive default values, or a catalog of values established for common local geomaterials. Target moduli should be set in conjunction with establishing the design moduli, with consideration of the moisture content at the time of compaction and the state of stress imparted by the testing technology to the geomaterial layer.

Field moduli should be measured during construction with an appropriate technology to ensure that the target modulus has been achieved. The technology used for this purpose should have the following attributes:

- Able to measure a fundamental property of materials (i.e., modulus),
- Sensitive enough so that poor- and high-quality final product can be readily delineated,

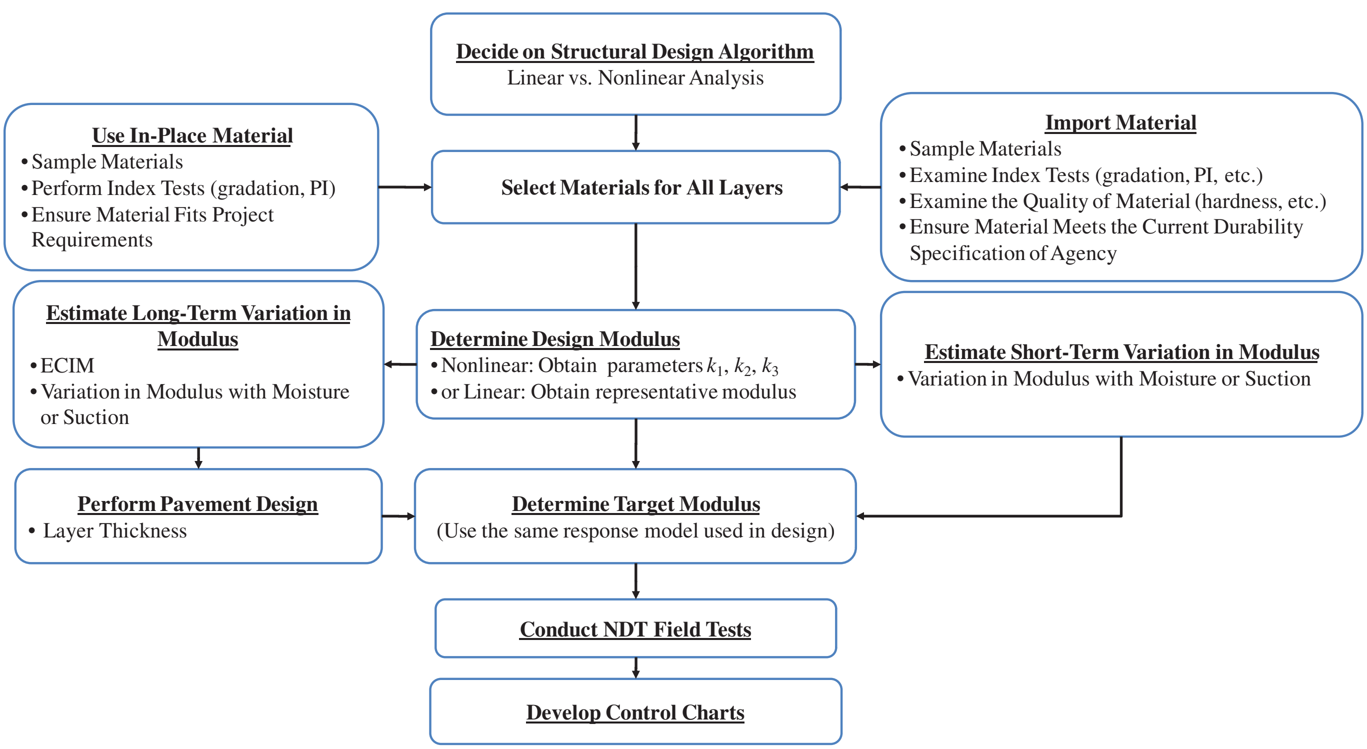

Figure 1 An ideal flowchart of a modulus-based specification.

- Accurate enough to provide meaningful feedback to the pavement designer, and
- Precise enough so that it can be confidently used in the acceptance process.

Appropriate statistical analysis (e.g., using control charts) should be carried out to ensure that the modulus and its variability along the project are in control. Appropriate tolerances should be allowed based on the uncertainties in establishing the target modulus and measurement technology to minimize the occurrence of disputes between the contractor and the highway agency. The process described above set the goal for the research conducted to develop the proposed specification located in the Appendix herein.

RESEARCH APPROACH

To address the objective and goals of the project, the research was conducted in three phases.

Phase I

Phase I consisted of documenting, synthesizing, prioritizing, and conducting gap analyses on the following topics:

1. National and international state of practice in modulus-based quality management;
2. Technologies for rapidly measuring relevant field parameters for a modulus-based specification;
3. Site variability in terms of material, moisture, thickness, and compaction inconsistencies;
4. Long-term moisture content variation models; and
5. Modulus-moisture content prediction models.

The main outcome of Phase I activities was a comprehensive work plan for developing and validating a practical yet scientifically sound specification by:

- Identifying the most relevant parameters that should be included in the specification;
- Recommending practical, desirable tolerances for relevant parameters;
- Suggesting the most appropriate technologies for rapidly measuring relevant parameters; and
- Establishing the optimum frequency of measurement of each parameter that balances the risks of highway agencies and contractors.

Phase II

Phase II implemented the Phase I work plan to develop the specification. It included laboratory, small-scale, and controlled field testing programs. This three-pronged approach was followed to separate a number of complex and inter-related issues into several well-defined hypotheses that, when tested, can provide the bases for a practical and scientifically sound specification.

Laboratory Study

Laboratory tests were conducted under precise moisture contents and densities on specimens prepared from a half-dozen geomaterials. These results provided a database to address issues key to development of the specification including:

- Determining moduli and their variation with moisture under constant compaction energy,
- Validating selected modulus-moisture relationships,
- Evaluating the impact of moisture content at the time of compaction on modulus, and
- Analyzing the effects of soil suction and moisture content on modulus.

Small-Scale Study

Four 3-ft-diameter by 2-ft-deep specimens were constructed from each geomaterial. The moisture contents and densities of all layers were strictly controlled. These experiments established the impact of several construction-related parameters on the modulus. In addition, the specimens were used to:

- Establish characteristics (repeatability and reproducibility) of the technologies and devices used to measure modulus and moisture,
- Establish a direct relationship between field and laboratory moduli at the same moisture and density conditions, and
- Calibrate structural models with data collected from sensors embedded in the specimens.

Field Study

Variability during actual field construction cannot be considered in small-scale specimens. To address this variability in the development of the specification, a 180-ft-long field section constructed at the Pavement Research Facility of the Louisiana Transportation Research Center (LTRC) was divided into three subsections with optimum moisture content (OMC), OMC−2%, and OMC+2%. The variability in the in-situ density and moisture content of each subsection was compared with the corresponding variability of modulus-based tests. In addition, the utility of the initial draft of the proposed specification was evaluated.

Phase III

In Phase III, the proposed specification was validated and fine-tuned through its evaluation on five field projects. The projects were distributed among the four environmental regions of the United States in order to include as many different geomaterial types, environmental conditions, and construction and quality control procedures as possible. Phase III activities were carried out in two stages.

Stage I consisted of testing the specification on three projects, documenting its shortcomings, and making necessary adjustments and improvements. In this stage, the research team collected relevant field data, conducted proposed laboratory tests, performed appropriate analyses, and compared the results with the proposed specification.

Stage II consisted of validating the specification as a shadow specification on two field projects. The research team worked hand-in-hand with the state highway agencies to implement the specification by (1) training agency personnel to conduct the tests (if needed), (2) leaving the equipment with them to collect data and interpret the results, and (3) obtaining the opinion of the agency personnel on the specification's practicality, performance compared to the state highway agency standards, and needed improvements.

Project Final Report

The complete project final report, which presents extensive discussions of the Phase II and Phase III laboratory and field testing programs and their results and analyses, is available on the TRB website (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2908) for download. The report includes twelve appendices:

- Appendix A: Proposed Modulus-Based Specification
- Appendix B: Tools for Quality Acceptance
- Appendix C: Online Highway Agencies' Survey for NCHRP Project 10-84
- Appendix D: Process for Converting Nonlinear Parameters from MEPDG Model to Ooi's Model
- Appendix E: Impact of Moisture Variation on Modulus-Based Device Measurements (Small-Scale Study)
- Appendix F: Evaluation of Numerical Models with Experimental Response of Pavement Through Small-Scale Testing
- Appendix G: Field Evaluation at Louisiana Transportation Research Center
- Appendix H: Observations from Implementation of Specification—Site I.1
- Appendix I: Observations from Implementation of Specification—Site I.2
- Appendix J: Observations from Implementation of Specification—Site I.3
- Appendix K: Observations from Implementation of Specification—Site II.1
- Appendix L: Observations from Implementation of Specification—Site II.2

SUMMARY OF RESULTS

Phase I

In Phase I, the relevant worldwide engineering and soils science literature on the following topics was reviewed, analyzed, and summarized:

- National and international state of practice in modulus-based quality management,
- Opportunities for and obstacles to the adoption of a modulus-based specification by the state highway agencies,
- Technologies for rapidly measuring relevant field parameters for a modulus-based specification, and
- Relevant modulus-moisture content prediction models.

An online survey found that state highway agencies were interested in implementing a practical modulus-based specification. At the same time, though, there was a lack of enthusiasm for incorporating laboratory resilient modulus and the principles of unsaturated soil mechanics into such a specification.

The literature review and survey identified the following NDT technologies as viable options for measuring the modulus of geomaterials:

- Dynamic cone penetrometer (DCP),
- Electro-mechanical stiffness (e.g., the Geogauge),

- Lightweight deflectometer (LWD), and
- Ultrasonic surface wave (e.g., the Portable Seismic Property Analyzer (PSPA)).

Similarly, the following technologies were identified as viable options for measuring the moisture content of geomaterials:

- Nuclear density gauge (NDG),
- Electrical impedance spectroscopy (e.g., the Soil Density Gauge (SDG)),
- Pressure rise (e.g., the Speedy Moisture Tester (SMT)), and
- Dielectric permittivity (e.g., the Road-Bed Water Content Meter (DOT600)).

Phase II

Three fine-grained soils (CL, CH, and ML), two sandy materials (SC and SM), and two unbound granular base materials (GW and GP) were selected as standard materials for Phase II. These materials exhibit a variety of behaviors in terms of their interactions with moisture and their use as compacted geomaterials.

Laboratory Testing Program

The objectives of the laboratory study were to determine (1) the impact on modulus of moisture content at the time of compaction, (2) the impact on modulus of moisture content at the time of testing relative to the moisture content at the time of compaction, and (3) modulus tolerances to accommodate less than 100% relative compaction.

More than twenty laboratory resilient modulus (MR) and free-free resonant column (FFRC) tests were performed on specimens from each geomaterial at different moisture contents and densities. The resilient moduli and the FFRC moduli were then correlated.

Impact of Moisture Content at Time of Compaction on Modulus. NCHRP's Mechanistic-Empirical Pavement Design Guide (MEPDG), now available from AASHTOWare as the Pavement ME Design, recommends an environmental factor (F_{env}) to adjust the MR for any degree of saturation other than the degree of saturation at the OMC (S_{opt}). Cary and Zapata (2010) proposed a form of the MEPDG equation that incorporates the Plasticity Index (PI) and the percentage passing the #200 sieve (*w*) in their predictive model. The Cary and Zapata curve for wPI = 0 predicted the moduli better than either the MEPDG or the general Cary and Zapata model with a corresponding wPI for each material. The normalized moisture content (defined as the difference between the compaction moisture content and the OMC divided by the OMC) also provided a reasonable correlation between the modulus and moisture.

Impact of Moisture Content at Time of Testing on Modulus. The change in the dry density of a compacted layer may be minimal as the time between the compaction and the testing increases. However, the modulus of the same layer may change significantly in that same period. Several specimens of each material were compacted at different moisture contents to a constant density equal to the maximum dry density (MDD) and dried to 0.7 OMC. In general, it was found that the greater the difference between the compaction and testing moisture contents, the greater the modulus. Neither the MEPDG nor the Cary and Zapata relationships could explain the trends in these data. A nonlinear estimation process was employed to find the optimum values of regression constants in the MEPDG equation for this condition. An alternative to the MEPDG equation was also proposed in terms of the difference between the compaction and testing moisture contents. Both models are promising but they require future refinement with more materials.

Tolerances to Relative Compactions less than 100%. Several specimens from each material were prepared at nominal relative compactions of 96%, 98%, and 100% of MDD. All specimens were compacted at the OMC. In general, the variation in moisture content influences modulus more significantly than the variation in density.

Incorporation of Unsaturated Soil Mechanics in the Protocol. A series of laboratory tests showed that the resilient moduli obtained from suction-controlled MR testing were close to those from standard MR testing for the same stress states. The closeness of those results indicated that the standard resilient modulus testing was sufficient for soils. Considering that periods of up to several weeks were needed to equilibrate the desired soil suction prior to MR testing, the standard method was proposed for testing soils. Soil-water characteristic curves can be used to estimate soil suction of the soil samples to address the variation in MR with suction.

Small-Scale Testing Program

The objectives of the small-scale testing program were to:

- Establish relationships among density, moisture content, and the parameters measured with the modulus-based devices.
- Relate field and laboratory moduli under controlled conditions.
- Evaluate how well the moisture-modulus relationships developed from laboratory specimens represent the field values under similar moisture content and density.
- Establish the repeatability and reproducibility of the selected modulus and moisture testing technologies.

Four unique 3-ft-diameter specimens were prepared from each geomaterial. Three specimens were compacted to MDD but at different moisture contents (nominally OMC, 1.2 OMC and 0.8 OMC). The fourth specimen was compacted at OMC but at a density equal to 96% of MDD. All specimens were placed on a similar subgrade.

Impact of Compaction Moisture Content. Average moduli measured on the small-scale specimens with the DCP, LWD, ultrasonic surface wave, and electro-mechanical stiffness technologies were superimposed on the Cary and Zapata and MEPDG moisture-modulus relationships. The MEPDG relationship for fine-grained soils was the most appropriate relationship for wet materials. The Cary and Zapata relationship with wPI = 0 described the moisture-modulus relationship for very dry materials reasonably well. This pattern points out the importance of moisture content process control during field compaction. The moduli were reasonably well correlated to the normalized moisture content, defined as the difference between the moisture contents at the time of testing and at compaction divided by the OMC.

Impact of Density. A clear pattern was not observed from the data. In many instances, the moduli at relative compactions of 100% and 96% were similar. The GP and GW base materials exhibited more sensitivity to relative compaction in the laboratory than in the small-scale tests. Overall, the variation in moisture content influenced modulus more significantly than the change in density.

Relationship Between Field and Laboratory Moduli. When the moisture contents were close to the compaction moisture contents in laboratory testing, the field moduli were greater than the laboratory moduli. This indicated that shortly after compaction, the field moduli are greater than the corresponding laboratory moduli. As the compacted materials were allowed to dry, the field moduli progressively became less than the corresponding laboratory moduli. As such, the specification should consider the timing between field measurements and completion of compaction. A relationship that can adjust the field moduli based on measured laboratory moduli was proposed. This relationship works well when the moisture content at the time of compaction is reasonably close to the moisture content at the time of testing.

Evaluating Tools for Quality Management. The selected technologies were evaluated based on their applicability to the goals of this project, their suitability, and their practicality. The DCP and LWD ranked highest in terms of practicality. Application of the ultrasonic surface wave technology permits direct, layer-specific modulus measurements. Among the moisture measurement technologies, the pressure rise technology appeared most feasible. Available testing devices based on the electrical impedance spectroscopy and dielectric permittivity technologies were also promising, but they need further development, especially in the area of pre-testing calibration.

Evaluation of Modulus-Based Devices. To evaluate the repeatability and reproducibility of the testing technologies, more than twenty similar specimens were prepared and tested. Using analysis of variance (ANOVA), the following conclusions were drawn:

- The contribution to variability of non-uniform changes in specimen properties between the time of construction and testing was similar among the technologies.
- The LWDs tested were more repeatable than the devices using ultrasonic surface wave and electro-mechanical stiffness technologies.
- The contribution of reproducibility to the total variability was greater for the Dynatest LWD and the device using the electro-mechanical stiffness technology; this indicates that the operator-device-specimen interaction may be more critical for these devices.

To investigate the variability of each modulus-based testing technology with composite pavement layers, repeatability tests were conducted on the top of the twenty small-scale specimens after their corresponding geomaterial layers were compacted. On average, the coefficient of variation (COV) of the device using ultrasonic surface wave technology was 15%, while the COVs of the LWDs and the device using electro-mechanical stiffness technology were about 7%.

The sensitivity of the technologies to changes in moisture content was also studied by comparing the average moduli from tests performed after the geomaterial layers were placed in the small-scale specimens. The moduli measured through ultrasonic surface wave technology were more sensitive to change in moisture content than the other technologies because those technologies provide a composite modulus of the geomaterial and underlying subgrade rather than the modulus of the geomaterial layer alone obtained with the ultrasonic surface wave technology.

Evaluation of Moisture Devices. To evaluate the moisture devices, twenty-five additional small-scale specimens were prepared from each geomaterial at five nominal moisture contents (OMC, 1.1 OMC, 1.2 OMC, 0.9 OMC, and 0.8 OMC). Based on an ANOVA, 86% of the total variation in measurements could be attributed to the repeatability of the devices. The combined variability (repeatability plus reproducibility) of the devices was material dependent The device using electrical impedance spectroscopy technology was the least material dependent and the most repeatable, but the least sensitive to the changes in moisture content. The repeatability of the other technologies was acceptable. All the technologies exhibited acceptable reproducibility.

In general, the biases of all the technologies increase as the soil becomes wetter and more plastic. The device using pressure rise technology was the most accurate. The bias values for the devices using electrical impedance spectroscopy and dielectric permittivity for each individual material were linearly related to the oven moisture content.

Numerical Modeling. A response algorithm was used to compare the experimental and numerical results from the small-scale specimens and develop the target values for different modulus-based testing technologies and transfer functions between the target and field moduli. A modified version of the MEPDG nonlinear resilient modulus model was utilized to calculate the variations in modulus of each layer. The observed differences between the measured and numerical results could be related to the differences in the laboratory and field moduli of the materials. An adjustment factor based on seismic measurements was proposed to accommodate the differences between laboratory and field stiffness.

Selecting Target Moduli. Setting the target moduli for the ultrasonic surface wave testing technology is relatively straightforward because it provides layer-specific moduli. Since the LWD and electro-mechanical stiffness technologies measure the surface responses to provide effective moduli of the pavement system, the establishment of their target moduli required the use of the calibrated numerical algorithm discussed in the previous section. The target value for the LWD for a one-layer pavement system was related to the plate diameter, applied surface stress, and the stiffness parameter k_2 of the geomaterial layer obtained from laboratory MR tests. An artificial neural network model was developed to estimate the LWD target moduli for two-layer pavement systems as a function of Poisson's ratios and MR nonlinear parameters k_1, k_2, and k_3 of both layers, the surface stress, and the thickness of the top layer. The target modulus of the device using electro-mechanical stiffness technology on a one-layer pavement system was related to the laboratory MR nonlinear parameters k_1 and k_2. For a two-layer pavement system, the target modulus was dependent on the top layer thickness and the k_1 parameters of the top and underlying layers.

The target moduli for both the LWD and electro-mechanical stiffness technology devices are impacted by the modulus parameters of the subgrade layer. For example, the change in the LWD target modulus is proportional to the power of 0.41 of the representative MR modulus of the top layer for a 6-in.-thick layer and proportional to the power of 0.61 for a 12-in.-thick top layer. The target moduli for the electro-mechanical stiffness device were normally about 1.8 times greater than target moduli from the LWD because of significant differences in the states of stress and the loading patterns for the different devices.

Field Testing Program

Field variability during construction brings another level of uncertainty to the process of specification development. This uncertainty was addressed during the field testing program to determine:

- How the repeatability and reproducibility of the selected modulus and moisture technologies vary between well-controlled small-scale tests and controlled full-scale construction.
- How field variability affects the relationship between field and laboratory moduli.
- How well the relationships among density, moisture, and the parameters measured with the modulus testing technologies held under actual construction.
- How well the moisture-modulus relationships developed from laboratory specimens represent the field values for similar moisture and density.

Two test sections (one section for subgrade and one for base layer) were constructed at the Pavement Research Facility of LTRC. Test sections were built with full-scale construction equipment to simulate normal highway construction. Each section was divided into three subsections. The subsections were constructed from the same material but their moisture contents varied from dry of OMC to OMC to wet of OMC. The moisture-density properties of compacted geomaterials were measured with nuclear density gauges and an electrical impedance spectroscopy device. The moduli of the compacted base and subgrade sections were estimated with DCP, LWDs, and devices based on the ultrasonic surface wave and electro-mechanical stiffness technologies. Soil samples were transported to the laboratory to measure their index properties, and to perform MR and FFRC tests.

The device based on electrical impedance spectroscopy technology exhibited high variability in the moisture and density estimation, especially on the base layer. Among devices for measuring stiffness or modulus, those based on electro-mechanical stiffness technology produces estimates of the field modulus that exhibited high uncertainty. These two technologies were de-emphasized during Phase III of the study. Based on replicate tests, the device using ultrasonic surface wave technology was the least repeatable on the subgrade layer, while the LWDs had the highest variability on the base layer.

Investigating the modulus-moisture correlations, the DCP and the ultrasonic surface wave technology device followed the MEPDG model (for fine-grained soils). The LWDs followed the Cary and Zapata model (with PI = 0) except for tests conducted dry of the OMC. The proposed model for correlating normalized modulus (M/M_{opt}) with normalized moisture content [(MC – OMC)/OMC] gave a better match to the field data.

Modulus-based acceptance scenarios were evaluated and compared with traditional density-based scenarios. Although most test sections passed the density-based acceptance limit, not all sections passed the modulus-based limit. The proposed process for estimating the target moduli seemed reasonable. The established field target moduli for the LWD and the ultrasonic surface wave technology device are dependent on the Poisson's ratios selected for compacted geomaterials.

The program of controlled field testing at LTRC confirmed the importance of observing the moisture contents of compacted layers, both at the time of compaction and at the time of testing. The anticipated field moduli adjusted for moisture content were reasonably close to the measured moduli as long as the Poisson's ratio was adjusted for change in moisture content. The uniformity of the underlying layers and their moduli affect the acceptance process with the LWD; the specification must address this finding.

Modulus-Based Specification

Based on the findings from the laboratory and small-scale, controlled field studies, a proposed modulus-based specification titled "Proposed Standard Specification for Modulus-Based Quality Management of Earthwork and Unbound Aggregates" (Appendix) was developed. The specification addresses the following key requirements: (1) relating acceptance to a structural design algorithm, (2) accepting materials for durability and constructability, (3) selecting target modulus, and (4) performing field measurements and acceptance.

Phase III

In Phase III, the specification developed in Phase II was evaluated on five field projects in two stages. The research team conducted all testing on the three Stage I projects; testing on the two Stage II projects was conducted by state highway agency personnel in close collaboration with the research team.

The first two Stage I projects consisted of constructing sections at different moisture contents (dry of OMC, OMC and wet of OMC) to study the impact of moisture and density variation on the implementation of the proposed specification. Other field projects followed the routine construction practices of the respective state highway agencies.

In general, the findings, conclusions, and lessons learned from Phase III agree with those from Phase II. Highway agencies evaluating the proposed specification for possible future adoption should carefully consider the following:

- Adoption of a modulus-based specification needs to be approached in the context of the levels of uncertainty associated with the current, well-established density-based specification criteria (especially when nuclear density gauges are used). This research has demonstrated that the quality of construction—defined as achieving adequate layer modulus—is often only weakly associated with achieving density.
- The Cary and Zapata (2010) modulus-moisture model and its variations are reasonable. The proposed model correlating normalized modulus (M/M_{opt}) with normalized moisture content [(MC – OMC)/OMC] matched the field data better.
- The most consistent results are obtained when moisture content measurements are carried out in conjunction with the modulus-based measurements.
- Modulus-based acceptance should be implemented in conjunction with a reasonably strict process control since variation in the moisture content and material indices significantly affect the measured moduli. The density and moisture measurements can be perhaps considered as process control items, with modulus-based measurements being used for quality acceptance.
- Due to large diversity in construction practices and material types across the United States, future implementation of the proposed specification by the state highway agencies will require calibration studies to adopt the specification to local materials and construction practices.
- The research identified several technologies and commercial devices for measuring modulus and moisture content that, on balance, provided acceptable performance. However, none of the technologies and related devices are close to perfect, and the proposed specification is not tied to the use of any specific technology or device. State DOTs should select specific technologies and devices on the basis of their own experience and judgments of practicality, cost, precision and accuracy, ease of use, etc.

FINDINGS, CONCLUSIONS, AND LESSONS LEARNED

The appendix presents a proposed specification for modulus-based acceptance titled "Proposed Standard Specification for Modulus-Based Quality Management of Earthwork and Unbound Aggregates."

Relating Acceptance to Structural Design Algorithm

The structural response algorithms used in this study are discussed in Chapter 6 of the project final report. Those response algorithms are quite similar to the response algorithms contained in the MEPDG. The MEPDG advocates two structural models (layered elastic and nonlinear finite element). As demonstrated in Section 6.2, the nonlinear algorithm seems more appropriate for estimating the behavior of compacted geomaterials under several modulus-based devices. A nonlinear structural model that approximates the response of layered geomaterials in testing with most modulus-based devices has been recommended and calibrated for LWDs and plate load tests.

Aside from the structural response algorithms, the material models in the MEPDG are relevant to this research. A modified version of the MEPDG nonlinear material model (Ooi et al., 2004) in the form of Equation 1 seems to yield more representative responses of the modulus-based devices than the model recommended by the MEPDG in Equation 2.

$$MR = k_1' P_a \left(\frac{\theta}{P_a} + 1\right)^{k_2'} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3'} \quad \text{(Eq. 1)}$$

$$MR = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \quad \text{(Eq. 2)}$$

This change entails practical problems for state highway agencies that utilize the MEPDG material model, and Appendix D of the final report provides relationships to convert parameters k_1 through k_3

recommended by the MEPDG to k_1' through k_3' utilized in this study.

Finally, it is emphasized that different resilient modulus test protocols (e.g., T 307-03 and NCHRP 1-28A) may yield different nonlinear parameters k_1 through k_3. The relationships provided here are based on AASHTO T 307-03. The proposed relationships in the specification and test methods should be recalibrated by highway agencies that use other test protocols.

Acceptance of Materials for Durability and Constructability

Achieving an adequate modulus does not guarantee a durable compacted geomaterial. To ensure durability, the selection of the material to be used in a construction project should be based on parameters such as hardness, gradation, and plasticity of the material. The requirements espoused by different highway agencies for this purpose are extremely diverse. Highway agencies can incorporate their own requirements since they can add their wealth of local experience with the available geomaterials and construction practices.

Selecting Target Modulus

Sections 6.5 and 6.6 of the project final report contain a process to select target moduli for devices that measure the response of the geomaterials. The nonlinear algorithm described in Section 6.2 was used to develop straightforward relationships for estimating field target moduli from resilient modulus parameters (k_1 through k_3) for a uniform layer of compacted geomaterial.

The MEPDG uses a three-tier hierarchical design approach (Level I through Level III). The proposed modulus-based specification is perhaps most appropriate for Levels I and II, which incorporate laboratory testing to estimate the material properties. Parameters k_1 through k_3 should preferably be determined from laboratory tests on the geomaterial sampled from the site, but the specification also provides an option for estimating these parameters from index properties of the geomaterial.

A neural network algorithm is provided for estimating the target moduli of two-layer systems. However, the most appropriate approach (especially for multi-layer earthwork) is to directly utilize the nonlinear algorithm described in Section 6.2 of the project final report.

Performing Field Measurements and Acceptance

A key concern with a modulus-based specification is the variability of the modulus measurements. Figure 2 compares measured moduli from well-controlled small-scale studies with the corresponding target moduli to demonstrate such variability. The sources of the apparent variability can be traced to the following parameters:

1. Inherent variability of the measurement devices,
2. Moisture content at the time of compaction,
3. Moisture content at the time of testing,
4. Relative compaction of the compacted geomaterial, and
5. Inherent differences in the laboratory and field moduli even when specimens are prepared at the same density and moisture content.

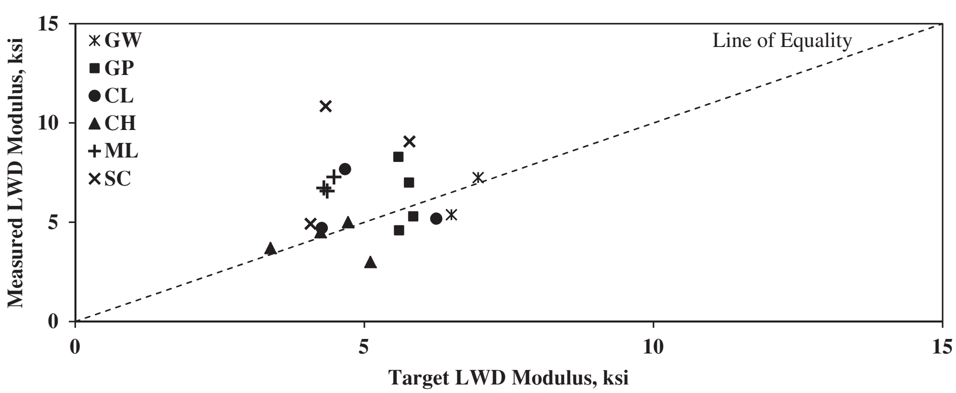

Figure 2 Comparison of target and field moduli with an LWD.

Based on tests on twenty independent specimens, the repeatability of the various modulus-measuring devices used in this research is better than 15% and their reproducibility is better than 12%. More than 70% of variability measured with these devices can be attributed to the variation in the properties of the materials. Based on this analysis, the acceptance threshold in the specification is preliminarily set at 80% of the calculated target modulus.

The moisture content at compaction significantly influences the modulus of the geomaterials. Depending on the type of geomaterial, a ±2% variation in the compaction moisture content may result in a variation of up to a factor of 3 in modulus.

Evidence of the importance of considering the moisture content at the time of testing relative to the moisture content at the time of compaction is provided in Section 3.4 of the project final report, including preliminary relationships to adjust the measured field moduli to a reference moisture content. The proposed relationships become less effective when the compaction moisture content significantly deviates from the OMC (especially when the material is placed wet of OMC), and when the field test is delayed significantly (significant difference between the compaction and testing moisture contents).

Lessons Learned from Evaluation of the Modulus-Based Specification

Material Selection

Adequate stiffness does not guarantee adequate durability of the material. The following items should be considered in specifying the types and nature of the geomaterials for different layers:

- Depending on the geographical location and the availability of materials, different highway agencies have different gradation and index property requirements for the geomaterials to be used in their areas. Agencies may replace Section 4 of the specification with their own definitions of permissible types of geomaterials.
- A geomaterial's moisture-density (M-D) curve has been used for decades by highway agencies and contractors to achieve a reasonable quality of earthwork. Different agencies use different compaction methods or energy to obtain the M-D curve. The specification should clearly define the compaction method and energy for different materials. The same compaction method should be used for preparing specimens for subsequent strength and modulus testing.

Placing and Mixing of Materials

An attraction of a modulus-based specification is not having to deal with nuclear density gauges, since achieving adequate modulus or stiffness supersedes density and moisture content requirements. One impediment to highway agencies implementing modulus-based specifications is that contractors know how to achieve a certain density but they do not know how to achieve a certain modulus. Based on these insights, the following remarks are offered:

- Layer modulus is a more rational and sensitive indicator of the quality of construction. A number of material- and construction-related parameters influence the modulus of a layer. Based on the field study carried out in this project, a reasonably rigid process control will go a long way toward achieving a uniform and acceptable quality compacted layer.
- Until contractors become experienced with modulus specifications, it may be prudent to use the density and moisture content as process control items.
- The moisture content at the time of compaction has a significant influence on the modulus of the compacted geomaterials. It is important to control the moisture content before compaction as discussed in Section 6.4 of the specification.
- It is prudent to achieve a certain density before acceptance testing. Less rigid density requirements (as compared to densities used for acceptance) are proposed in Section 6.5 of the specification.
- One prudent means of process control is the use of the intelligent compaction (IC) technology instead of density. IC technology, if used properly, ensures the uniformity of the layer.
- The fastest way to obtain uniform and acceptable quality is to ensure that the first layer of the embankment or pavement foundation is compacted uniformly and solidly. Any lack of uniformity in the first layer will propagate throughout the lifts placed at a job site, especially when the devices that measure the system's response (such as LWDs) are used.

Quality Acceptance

Several inter-related aspects of quality acceptance require further comment.

- The timing of modulus-based acceptance testing relative to the completion of compaction is much more critical than for density-based acceptance testing. As this research demonstrates, the modulus of the compacted geomaterial increases significantly with time, as the material becomes drier. As such, modulus-based testing should be carried out as close to the completion of compaction as possible. To discourage delay between the time of testing and compaction, the specification introduces the concept of moisture-adjusted modulus, where the modulus is adjusted to one reference moisture content (i.e., moisture content at the time of compaction). In addition, limits are proposed for the delay in testing in terms of reduction in moisture content of the material.
- The minimum number of tests for acceptance has been set based on limited precision and bias tests. These values can be modified based on the experience of the state highway agencies.
- The acceptance method and basis for payment should be specified by each highway agency based on its institutional preference and shadow specifying with the modulus-based specification on several trial projects.

Target Modulus Selection

A new algorithm is proposed for setting the target modulus. This algorithm considers the nonlinear parameters of the geomaterial being tested in a way that is compatible with the design process. The following advice is based on experience in this research:

- The accuracy of the target modulus is directly related to the sophistication of the response model used in the design and the effort expended in characterizing the materials in the laboratory.
- The proposed modulus-based specification is perhaps most appropriate for a Level I MEPDG pavement design where laboratory testing is conducted to estimate the required material properties (especially the parameters k_1 through k_3 from MR tests). However, the specification should also work reasonably well when a Level II design is conducted with material properties estimated from a catalogue of most common materials or from other sources.
- The proposed specification should be used with caution by state highway agencies that conduct pavement design using empirical methods or use default material models provided in the mechanistic-empirical design methods. In those cases, the concept of using a test strip to set the target modulus empirically should be considered. Such an approach would provide the potential modulus of the layer that may be different from the design modulus.
- A material's Poisson's ratio can substantially influence the target modulus and therefore the acceptance rate. The specification provides a set of recommended Poisson's ratios that are directly compatible with the MEPDG recommendations. The state highway agencies should evaluate these values for compatibility with their materials. As a general guideline, the assumed Poisson's ratio should be increased if the contractor tends to place the material wet of OMC and decreased if the contractor tends to place the material dry of OMC.

REFERENCES

Cary, C.E., and Zapata, C.E. (2010). Enhanced Model for Resilient Response of Soils Resulting from Seasonal Changes as Implemented in Mechanistic-Empirical Pavement Design Guide. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2170,* Transportation Research Board of the National Academies, Washington, D.C., pp. 36–44.

Ooi, P.S.K., Archilla, A.R., and Sandefur, K.G. (2004). Resilient Modulus Models for Compacted Cohesive Soils. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1874,* Transportation Research Board of the National Academies, Washington, D.C., pp. 115–124.

APPENDIX

PROPOSED STANDARD SPECIFICATION FOR MODULUS-BASED QUALITY MANAGEMENT OF EARTHWORK AND UNBOUND AGGREGATES

AASHTO Designation M XXX

1. SCOPE[1]

This specification covers the quality management of compacted geomaterials with modulus-based methods. This specification pertains to construction of embankments and pavement layers such as prepared subgrade, subbase, and base without stabilizing agents.

2. REFERENCED DOCUMENTS

AASHTO Standards:

- M 57, Materials for Embankments and Subgrades
- M 147, Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses
- T 2, Sampling of Aggregates
- T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 99, Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop
- T 180, Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop
- T 217, Determination of Moisture in Soils by Means of a Calcium Carbide Gas Pressure Moisture Tester
- T 265, Laboratory Determination of Moisture Content of Soils
- T 310, In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods

3. DEFINITIONS

3.1. Lift: Lift is a unit of material within a layer that is placed for compaction.
3.2. Layer: Layer is the total thickness for each material type and may comprise one or more lifts.
3.3. Optimum Moisture Content[2]: The optimum moisture content is determined by the Standard Proctor Density Method (AASHTO T 99) or Modified Proctor Density Method (AASHTO T 180).
3.4. Maximum Dry Density[2]: Maximum dry density is determined by AASHTO T 99 or AASHTO T 180.

---

[1] The goal of the project was to migrate from density-based acceptance to modulus-based acceptance. Changes in the type and gradation of the materials and moisture content at compaction have significant impact on the modulus of the compacted geomaterials. As reflected in the accompanied report, a reasonably rigid process control will ensure a uniform and high-quality final product.

[2] This is the practice carried out as part of this study. The state highway agencies (SHAs) are encouraged to modify their local practices.

4. MATERIALS[3]

4.1. Unless waived or altered by the Engineer, materials shall conform to the requirements of the relevant specifications listed in Table 4.1.

Table 4.1 Material Specifications

Material	Specification[3]
Embankment	AASHTO M 57
Subgrade	AASHTO M 57
Subbase	AASHTO M 147
Base	AASHTO M 147

4.2. The Contractor shall produce, deliver, and stockpile materials at the designated sites as directed by the Engineer that conforms to the requirements in Table 4.1.
4.3. The Contractor shall be responsible for maintaining a gradation process control program in accordance with random sampling procedures in AASHTO T 2[3].
4.4. A change in material source without permission of the Engineer is prohibited.
4.5. The Contractor shall assume full responsibility for the production and placement of acceptable materials.

5. PLACING MATERIALS

5.1. Each lift of material should conform to Section 4 requirements.
5.2. Limit lift thickness by the capability of the equipment to uniformly blend and compact the entire lift.
5.3. Place adequate material in uniform lifts, parallel to the profile grade, over the full width of the roadway.
5.4. At the time of depositing the materials on the road, the roadbed shall be so compact that no rutting or displacement will occur.
5.5. Water shall be added or removed during mixing operations in the quantity necessary to yield proper compaction.
5.6. Uniformly blend the entire thickness of each lift before testing moisture content.
5.7. At the time of spreading the material, the material shall be so uniformly mixed that it meets specified gradation requirements.
5.8. The material for each lift shall be spread and compacted with adequate moisture content to the required cross section before placing the succeeding lift.
5.9. The surface of each lift shall be maintained until the next lift is placed.

6. CONTRACTOR QUALITY CONTROL

6.1. The Contractor shall develop a Quality Control Program which addresses all elements affecting the quality of the compacted geomaterials including but not limited to the following items:

- Material Uniformity as defined in Section 6.3
- Moisture Content at Compaction as defined in Section 6.4
- Minimum Density at Compaction as defined in Section 6.5

[3] SHAs can replace the AASHTO specifications and/or test methods with their own specifications and methods.

6.2. The Quality Control Plan shall indicate appropriate action that shall be taken when the process is out of control.

6.2.1. At the discretion of the Engineer, a proofing test section may be required for equipment calibration, establishment of compaction process, and demonstration of the feasibility of the Quality Control Program prior to initiation of the construction.

6.3. Material Uniformity[4]

6.3.1. Aggregate gradation compliance will be documented in accordance with Table 6.1. The Contractor shall correct the unacceptable material. Upon completion of any corrective work, whether by blending, mixing, adding and/or replacing material, the corrected material will be sampled and tested for compliance.

Table 6.1 Material Control Requirements

Material	**Percent Difference from Target Gradation**[5]			
	Sieve 1 in. (25.0 mm)	**Sieve No. 4 (4.75 mm)**	**Sieve No. 40 (425 µm)**	**Sieve No. 200 (75 µm)**
Embankment (if applicable)	10%	10%	10%	10%
Subgrade	10%	10%	10%	10%
Subbase	5%	8%	5%	3%
Base	5%	8%	5%	3%

6.3.2. The gradation of the material is determined as per AASHTO T 27 and/or T 11 or other method specified by the Engineer.

6.4. Moisture Content at Compaction[5]

6.4.1. The moisture content of the material at the time of compaction shall not be outside the permissible ranges in Table 6.2.

6.4.2. Compliance with moisture content will be documented before compaction as per AASHTO T 217 or other method specified by the Engineer.

6.4.3. Samples for moisture content testing will be taken randomly prior to compaction, in accordance with random sampling procedures contained in AASHTO T 2 or other method specified by the Engineer.

6.4.4. The Contractor shall rework the material that does not meet the specification to achieve the specified moisture content.

Table 6.2 Moisture Content Requirements

Optimum Moisture Content (OMC)	**Moisture Content**	
	Min.	**Max.**
<10%	OMC – 2%	OMC + 2%
≥10%	0.8 OMC	1.2 OMC

6.5. Minimum Density[4]

6.5.1. The full thickness of each lift shall be compacted to not less than the percentage of maximum density as reflected in Table 6.3.

[4] SHAs can replace the test methods and values with their own test methods and values.

[5] This item is extremely critical to the successful implementation of modulus-based specification. SHAs may consider tightening the requirements, if feasible.

6.5.2. Compliance with moisture content will be documented before quality acceptance as per AASHTO T 217 or other method specified by the Engineer.

6.5.3. Samples for density testing will be taken randomly prior to compaction, in accordance with random sampling procedures contained in AASHTO T 2 or other method specified by the Engineer.

6.5.4. The Contractor shall rework the material that does not meet the specification to achieve the specified dry density.

6.5.5. The density requirements can be waived by the Engineer, if the lift is compacted with instrumented rollers as per intelligent compaction concept.

Table 6.3 Relative Density Requirements for Compaction

Material	Min. Required Relative Density
Embankment	85% of Maximum Dry Density
Subgrade	90% of Maximum Dry Density
Subbase	95% of Maximum Dry Density
Base	95% of Maximum Dry Density

7. ENGINEER QUALITY ACCEPTANCE (QA)

7.1. The acceptance of the compacted lift is based on achieving adequate moisture-adjusted modulus when tested as per AASHTO T E1E[6] or other method specified by the Engineer.

7.2. The moisture content of the material at the time of modulus-based testing shall be measured as per AASHTO T 310 or other method specified by the Engineer.

7.3. Modulus measurements should be carried out in a timely manner and before the moisture content of the compacted layer falls below 1% (2% for materials with OMC >10%) of the moisture content measured at the time of compaction under Item 7.4[7].

7.4. The measured modulus shall be adjusted for the moisture content at the time of testing as specified in AASHTO T E1E or other method specified by the Engineer.

7.5. The Contractor shall rework the material that does not meet the specification to achieve the specified modulus. Upon completion of any corrective work, the corrected material shall be sampled and tested for acceptance.

7.6. Unless altered by the Engineer, compliance shall be documented in accordance with the minimum frequency of testing for modulus and moisture content reflected in Table 7.1[8]. This frequency can be reduced as justified by the use of continuous compaction control during the contractor's process control. Modulus/moisture content testing will be carried out randomly in accordance with random sampling procedures contained in AASHTO T 2.

Table 7.1 Minimum Schedule of Modulus-Based Tests

Material	Maximum Lot Size[7]	No. of Sublots[7]	No. of Tests per Sublot[9]
Embankment	4000 yd^2 (3400 m^2)	2	5
Subgrade	3000 yd^2 (2500 m^2)	2	5
Subbase	2400 yd^2 (2000 m^2)	2	5
Base	2000 yd^2 (1700 m^2)	2	5

[6] Light Weight Deflectometer
[7] Since modulus of a compacted layer increases significantly with time, this item is added to ensure that the acceptance is done in a timely manner.
[8] SHAs can replace the values in Table 7.1 with their own values.
[9] This value is derived from the variability analyses of the devices in this project.

7.7. Unless altered by the Engineer, moisture-adjusted modulus shall be evaluated for acceptance on a lot basis using the method of estimating percentage of material within specification limits (PWL)[10].

7.8. Unless altered by the Engineer, the lower specification tolerance limit for moisture-adjusted modulus shall be 0.8[11] times the target modulus specified in AASHTO T E1E. Unless altered by the Engineer, the Contractor shall target production quality to achieve 90 PWL or higher.

7.9. Unless altered by the Engineer, the lot shall be acceptable if the PWL of the lot equals or exceeds 50[12].

[10] SHAs may replace this method with other methods they currently use.
[11] This value is derived from the preliminary variability analyses of the devices in the report. SHAs can replace this value with their own value.
[12] This value seems to be common among most specifications. SHAs can replace this value with their own value.

Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

ISBN 978-0-309-30814-4

Subscriber Categories: Construction • Geotechnology • Materials

These digests are issued in order to increase awareness of research results emanating from projects in the Cooperative Research Programs (CRP). Persons wanting to pursue the project subject matter in greater depth should contact the CRP Staff, Transportation Research Board of the National Academies, 500 Fifth Street, NW, Washington, DC 20001.