Transportation Consortium of South-Central States

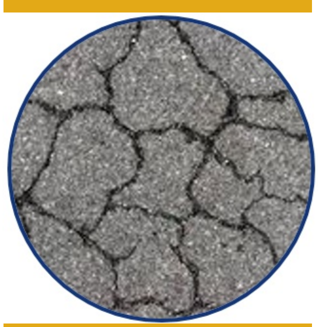
Tran-SET

*Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation*

# In-Situ Mechanical Characterization for Compacted Aggregates

**Project No. 17GTNMS02**

**Lead University: New Mexico State University**



**Enhancing Durability and Service Life of Infrastructure**

**Final Report**
**October 2018**

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**16. Abstract**

The evaluation of compacted unbound aggregate layers is perhaps the most common undertaking in transportation-related projects. The assessment of compaction compliance in engineered fills, subgrades, subbases, and bases in roadways and railways is central to ensure longevity of ground transportation infrastructure. In many cases, premature failures in roadways that originate in the unbound aggregate layers can be traced back to inadequate compaction. These failures are preventable, provided the problem areas can be identified by a suitable field test during construction. The most widely used method for compaction assessment during construction is the nuclear density gauge (NDG) test. While the device itself is easy to use, the complexity associated with the transportation and servicing of the radioactive device makes the test logistically and economically expensive. Furthermore, NDGs were designed to extract density and moisture content only, which are not sufficient to describe the mechanical performance of compacted unbound aggregates. This project was set out to identify available non-nuclear alternatives to the NDG test and evaluate if their failure to replace NDGs was traced to shortcomings that could be overcome through automation. It was found that the successful implementation of a non-nuclear, in-situ, mechanical performance evaluation test device requires satisfying the current information needs of practice in a system-wide context. Unavoidably, the device must be able to provide reliable density and moisture content measurements to fit within the established construction control regulatory framework, provide measurements of strength and stiffness to advance the state-of-the-practice, and be useful for the state department of transportation (DOT) in the transition from empirical to mechanistic analysis and design. Unfortunately, none of the available devices can provide on its own direct measurements of all of these parameters. In conclusion, automation may play a role in the design of a replacement for the NDG, but the real need lies in the development of a new transitional device that can measure density, moisture content, strength, and stiffness.

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## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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## ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| BCD | Briaud Compaction Device |
| CBR | California Bearing Ratio |
| CH | Clegg Hammer |
| CHM | Clegg hammer modulus |
| CIV | Clegg impact value |
| COV | Coefficient of variation or covariance |
| DC | Direct current |
| DCP | Dynamic Cone Penetrometer |
| EDG | Electrical Density Gauge |
| $e_{max}$ | Maximum void ratio |
| FHWA | Federal Highway Administration |
| $f_{pb}$ | Fraction of solid lead |
| $f_{lead\ shot}$ | Volume fraction of lead shot particles |
| $f_{lead\ wire}$ | Volume fraction of lead wire particles |
| FWD | Falling Weight Deflectometer |
| Hz | Hertz |
| $K_o$ | Lateral earth pressure coefficient at rest |
| LWD | Light Weight Deflectometer |
| $\lambda_T$ | Thermal conductivity |
| M | Small-strain constrained modulus |
| MDI | Moisture Density Indicator |
| MPa | Megapascal |
| μsec | Microsecond |
| NCHRP | National Cooperative Highway Research Program |
| NDG | Nuclear Density Gauge |
| NMDOT | New Mexico Department of Transportation |
| PR | Penetration rate |
| PSPA | Portable Seismic Property Analyzer |
| QC/QA | Quality control and quality assurance |
| $\rho$ | Bulk density |
| SDG | Soil Density Gauge |
| $\sigma_e$ | Electrical conductivity |
| SASW | Spectral analysis of surface waves |
| SPA | Seismic Property Analyzer |
| SSG | Soil Stiffness Gauge |
| SSV | Soil support value |
| USW | Ultrasonic surface wave |
| $v_p$ | p-Wave velocity |

## EXECUTIVE SUMMARY

The evaluation of compacted unbound aggregate layers is perhaps the most common undertaking in transportation-related projects. The assessment of compaction compliance in engineered fills, subgrades, subbases, and bases in roadways and railways is central to ensure longevity of ground transportation infrastructure. In many cases, premature failures in roadways that originate in the unbound aggregate layers can be traced back to inadequate compaction. These failures are preventable, provided the problem areas can be identified by a suitable field test during construction. The most widely used method for compaction assessment during construction is the nuclear density gauge (NDG) test. There are two primary issues with this device: it is radioactive and does not fully capture the mechanical performance of unbound aggregates. While the test itself is simple and robust, the complexity associated with the transportation and servicing of the radioactive device makes the test logistically and economically expensive. Furthermore, NDGs were designed to extract density and moisture content. While these parameters are still the norm in practice for compaction quality control/quality assurance (QC/QA), they do not provide the key mechanical properties needed for a mechanistic analysis of unbound pavement layers.

The state of the art in mechanical characterization of compacted aggregates continues to make significant progress, and the gap with the state of the practice in transportation geotechnics continues to widen. New in-situ testing technologies for compaction quality control continue to find resistance or serious challenges to adoption. The objectives of this study are to determine the overall end-user priorities for field characterization and control of compacted aggregates in the state of New Mexico, to evaluate the suitability of available non-nuclear devices to meet testing needs in this local context, and to explore technological advances that could lead to new, more suitable, means of recovering information for quality control.

The disconnect between the state of the art and the state of the practice is most evident in the testing priorities. Academics have abandoned density and moisture content in favor of more meaningful mechanical performance metrics such as strength and stiffness, yet practice (i.e., designers, inspectors, and contractors) values density and moisture content measurements the most. Thus, devices developed to measure strength and/or stiffness alone are ranked very low in practice. To understand the resistance to adoption of strength and/or stiffness measuring devices, one must understand that the NDG is part of a system. There is an associated regulatory framework (construction specifications) based on density and moisture content criteria. State inspectors and contractors have years of experience dealing with density and moisture content as acceptance criteria and with the NDG as the standard quality control test. Changing the device requires changes to the entire system that are faced with institutional inertia. Thus, there are numerous non-technical barriers to implementation.

The successful implementation of a non-nuclear, in-situ, mechanical performance evaluation test device requires satisfying the current information needs of practice in a system-wide context. Unavoidably, the device must be able to provide reliable density and moisture content measurements to fit within the established construction control regulatory framework. A non-nuclear device that measures density and moisture content accurately, rapidly, robustly and that can be as portable as an NDG will still face some institutional inertia related to lack of

familiarity by technicians and contractors, but would be the most likely candidate to replace the NDG. However, limiting such device to the determination of these two parameters (i.e., density and moisture content) will do nothing to advance the state of the practice in the in-situ mechanical characterization of compacted aggregates. Thus, the real need lies in the development of a transitional device that can measure density, moisture content, strength, and stiffness.

Devices that use electromagnetic stimuli to characterize compacted unbound aggregates are primarily used to determine density and moisture content. Conversely, devices that use a mechanical stimulus are used to determine strength and stiffness. Available devices that use thermal stimulus are only used to determine moisture content. While some devices claim to provide density, moisture content, strength, and stiffness measurements, these are obtained through the use of empirical correlations between these parameters. Extensive material-specific laboratory calibration is required to obtain the correlations necessary to estimate all parameters. Yet, sensitivity to small variations in material characteristics and/or environmental conditions could render the correlations invalid when testing in the field. Therefore, none of the devices reviewed as part of this study meets all of the requirements necessary to satisfy the needs of practitioners and to narrow the gap with the state of the art.

Research efforts should concentrate in the development of a transitional device capable of measuring directly the density, moisture content, strength, and stiffness of compacted aggregates. By providing side-by-side measurements of all properties, such a device could adapt to the current construction specifications without requiring changes to the business as usual. Inspectors and contractors would have access to real-time density and moisture content data in the field, so that they can still be able to use the pass-fail criteria with which they are familiar, and strength and stiffness data can also be recorded and made available to engineers and designers. Over time, the compiled data set could be used to develop progressive modifications to the regulatory framework, effectively phasing out density and moisture content evaluation criteria in favor of mechanical performance standards.

The development of such a device cannot rely on the use of a single stimulus but could draw from electromagnetic, thermal, and mechanical methods, and combine them into a self-contained portable device capable of directly measuring all parameters of interest. Of particular interest would be the incorporation of a device that could take advantage of the thermo-mechanical coupling discussed in section 3 of this report. Because no single device can be improved beyond its inherent physical limitations, automation alone cannot solve the problem. However, automation can, and needs, to be central to the development of any new device to minimize the need for operator input and optimize its performance under typical field conditions.

## IMPLEMENTATION STATEMENT

The initial plan for the implementation phase was to outline a plan to overcome the limitations of available test devices through automation. However, since it was found that no single device can be improved beyond its inherent physical limitations, automation alone cannot solve the problem. Instead, the implementation phase of this project will concentrate on the assessment of compatibility between different testing methods. This part the project will help inform the development of a new device that draws from electromagnetic, thermal, and mechanical stimuli to measure density, moisture content, strength and stiffness directly and with minimal need for calibration. By exploring the basic measurement requirements, the team will identify compatible electronics (sensors, controllers, data loggers, and communication systems), and create a blueprint for an automated prototype. The final outcome of the implementation phase will be a proposal for the development of the new device.

# 1. INTRODUCTION

The evaluation of compacted unbound aggregate layers is perhaps the most common undertaking in transportation-related projects. The assessment of compaction compliance in engineered fills, subgrades, subbases, and bases in roadways and railways is central to ensure longevity of ground transportation infrastructure. In many cases, premature failures in roadways that originate in the unbound aggregate layers can be traced back to inadequate compaction. These failures are preventable, provided the problem areas can be identified by a suitable field-test during construction. The most widely used method of compaction assessment during construction is the nuclear density gauge (NDG) test. There are two primary issues with this device: it is radioactive and does not fully capture the mechanical performance of unbound aggregates. While the test itself is simple and robust, the complexity associated with the transportation and servicing of the radioactive device makes the test logistically and economically expensive. Furthermore, NDGs were designed to extract density and moisture content. These parameters are still the norm in practice for compaction QC/QA; however, they do not provide the key mechanical properties needed for a mechanistic analysis of unbound pavement layers.

The shortcomings of the NDG test motivated the National Cooperative Highway Research Program (NCHRP) Synthesis 456 which focused on a review of non-nuclear methods for compaction control of unbound materials *(1)*. This synthesis of highway practices published in 2014 explored available non-nuclear alternatives for compaction control and material characterization. The study concluded that most of state transportation agencies across the nation still rely solely on density and moisture content to specify the compaction evaluation criteria. The synthesis also shows that in spite of a wide availability of field characterization tools that can offer reliable and relevant material properties for compacted unbound aggregates, none has been able to gain any traction, and that NDGs remain the standard of practice. However, over 50% of states surveyed in the 2014 NCHRP Synthesis study expressed an unsatisfied need for a non-nuclear device *(1)*.

The state of the art in mechanical characterization of compacted aggregates continues to make significant progress, and the gap with the state of the practice in transportation geotechnics continues to widen. New in-situ testing technologies for compaction quality control continue to find resistance or serious challenges to adoption. The authors hypothesize that the challenge is not entirely technical, but could rather be traced to a disconnect between the priorities and preferences of device developers (academics) and end-users (designers, inspectors, and contractors). Furthermore, the authors believe that automation could offer a clever solution to satisfy all parties. This study focuses on this gap and aims to advance the state of the practice by informing the development of future automated in-situ testing devices capable of satisfying the current and future compaction control testing needs of state transportation agencies.

## 2. OBJECTIVE

The long-term objective of the authors of this report is to improve the in-situ mechanical characterization of compacted unbound aggregates in transportation infrastructure to help speed up the transition from empirical to mechanistic pavement analysis and design. The development and adoption of reliable automated test devices are expected to help engineers optimize their designs while maintaining adequate reliability. Furthermore, the same devices would allow highway inspectors and contractors to identify deficiencies in mechanical performance during construction which could prevent premature failure of pavement structures. Findings from this study will serve as the starting point towards the development of novel mechanical characterization devices in tune with the needs of practitioners, inspectors and contractors, and capable of providing the information required by pavement designers.

The specific objectives of this study are to determine the overall end-user priorities for field characterization and control of compacted aggregates in the state of New Mexico, to evaluate the suitability of available non-nuclear devices to meet testing needs in this local context, and to explore technological advances that could lead to new, more suitable means of recovering information for quality control.

## 3. SCOPE

This study focuses on density, moisture content, strength, and stiffness measuring devices reviewed in the NCHRP Synthesis 456 *(1)*. The analysis of suitability concentrates on the priorities expressed by NMDOT Materials Bureau personnel during meetings with the research team. Devices are introduced briefly, and only relevant information to the local context is included to avoid repeating unnecessarily information already available in the synthesis report. The study of available theories includes mechanical, electromagnetic, and thermal methods. In particular, this report examines a promising thermo-mechanical coupling in dry granular materials recently discovered by Dr. Cortes, see Findings Section 3. Finally, the scope of work does not include prototype development and testing; thus, automation recommendations are based on speculation. These recommendations are not conclusive but are rather meant to guide future research on equipment development.

## 4. METHODOLOGY

The NMDOT has experimented over the years with non-nuclear devices for construction control of compacted aggregates; however, none has been able to replace the NDG despite its shortcomings and limitations (i.e., it is radioactive and does not fully capture the mechanical performance of unbound aggregates). Thus, the first part of this project focused on engaging the NMDOT Materials Bureau, the group in charge of quality control testing for compacted aggregates, in a discussion to determine their priorities, and to establish a local context. The research team consulted with Kelly Montoya (Pavement Field Exploration Engineer), James Gallegos (State Materials Engineer), Brian Legan (Technician Training Certification Program Administrator), and Sean Brady (State Concrete Engineer). Dr. John C. Lommler (Geotechnical Principal Engineer at Wood), a local consultant who served in the technical panel, also provided insights to establish a sense of end-user experiences and needs.

Once a local context was established, the research team gathered information from the literature on test devices and proceeded to determine where the resistance to implementation was originating in each case. Theoretical advances relevant to the project were reviewed as well. This helped organize and present the review of test devices according to the underlying physical principles on which they work. The information gathered was used to separate inherent test limitations from operational test limitations. In cases were only operational limitations were found, the research team proceeded to explore hypothetically if automation could help overcome such limitations.

# 5. FINDINGS

## 5.1. Local Context

Discussions with NMDOT personnel and with the project technical panel about their experience with NDG devices and with alternative non-nuclear tests in New Mexico can be summarized as follows.

The NDG is the standard device used in the state of New Mexico for measuring the field density of compacted unbound aggregates. New Mexico state officials (NMDOT) and local consultants echoed the need for a suitable non-nuclear test device for quality control of compacted aggregates expressed by their peers in NCHRP Synthesis 456 *(1)*. The NMDOT faces the same challenges related to the use of NDGs. Namely, extensive regulations and prohibitive costs associated with the handling, storage, calibration, maintenance and transportation of NDGs. In addition, state officials pointed out that the NMDOT has acquired over the years a considerable number of NDG devices; thus, this capital investment and the cost of device decommissioning need to be considered when assessing the feasibility of adoption of a different device.

The NMDOT is regularly approached by device manufacturers that offer alternative non-nuclear testing devices. New Mexico has entertained the idea of switching from the NDG, and has conducted multiple trials with non-nuclear devices; however, none has been identified as a serious candidate to replace the NDG. The NMDOT Materials Bureau identifies the following priorities in order of importance when evaluating the merits of alternative devices:

1. Accurate and repeatable <u>measurements of density and moisture content</u>
2. Rapid testing time (from deployment to data processing)
3. Portability (same level of site accessibility as the NDG)
4. Robustness (calibration and maintenance needs)
5. Usability (number of operators and hours of training)
6. Mechanical performance data (strength and stiffness)

The disconnect between the state of the art and the state of the practice is evident in the list of priorities. Academics have abandoned density and moisture content in favor of more meaningful mechanical performance metrics such as strength and stiffness of the compacted aggregates, yet practice values density and moisture content measurements the most. Thus, devices developed to measure strength and/or stiffness alone are ranked very low in practice. To understand the resistance to adoption of strength and/or stiffness measuring devices, one must understand that the NDG is part of a system. There is an associated regulatory framework (construction specifications) based on density and moisture content criteria. State inspectors and contractors have years of experience dealing with density and moisture content as acceptance criteria and with the NDG as the standard quality control test. Furthermore, there are units within NMDOT in charge of training and certification of NDG technicians. Changing the device would require changes to the entire system, and these changes would be faced with institutional inertia. Thus, there are numerous non-technical barriers to implementation.

## 5.2. Review of In-Situ Testing Methods and Available Devices

### *5.2.1. Electrical Methods*

These methods employ electromagnetic stimuli to probe the material. An electrode inserted in the soil is used as a source to 'inject' the electromagnetic input (pulse or wave), and one or several other electrodes are used as receivers to measure the output signal. Differences between the input and output signals are the result of interactions between the electromagnetic wave and the medium. Electricity can flow through the solid particles alone, through the fluid alone, and through both (bridging). However, aggregate particles are poor conductors, so the majority of the energy transfer is mediated by the fluid. The total electrical flow depends on the density and moisture content; therefore, electrical methods have the potential to offer rapid and reliable means of evaluation of the compacted aggregate structure *(2)*.

However, electrical measurements in soils are challenging because the material interacts with direct and alternate currents in complex ways. In the case of direct currents, electro-kinetic couplings give rise to electro-osmosis and electrochemical effects that can induce irreversible changes in the material *(2)*. When alternating currents are used, the measured material response is frequency dependent. Furthermore, particle-size and mineralogical composition can alter the interaction between the material and the electrical stimulus; thus, devices intended for use in fine-grained soils (silts and clays) may not be readily compatible with coarse-grained aggregates such as those used in pavement base and subbase layers. In coarse-grained soils, electrical conductivity is primarily governed by moisture content and by the concentration of salts in the fluid. Thus, changes in the pore fluid concentration (electrolyte) can also affect measurements conducted using electrical methods.

Available devices focus on the determination of moisture content and density. Despite recent efforts to collect mechanical performance data from electrical measurements, there are still no reliable means of obtaining strength and stiffness *(3)*.

**Soil Density Gauge:** The soil density gauge (SDG) uses electromagnetic impedance spectroscopy to estimate the density and moisture content of unbound aggregates. The SDG uses an alternating current stimulus in the radio-frequency range ($10^1$~$10^9$ Hz) *(1)*. The configuration consists of a coaxial cable where there is a central electrode (source) surrounded by a ring electrode (receiver). The source and receiver are separated from the soil by an air gap. Thus, the electromagnetic stimulus travels from the source through air into the soil and back into the receiver. The measurement provides complex impedance spectra which are processed using a proprietary algorithm to estimate density and moisture content *(4)*. The primary limitation of the device is its inability to produce strength and stiffness measurements and its sensitivity to relatively small variations in particle gradation *(5)* (Table 1). Furthermore, operators need to have an intricate knowledge of the device to apply necessary corrections *(6)*.

**Table 1. Soil density gauge summary.**

| | |
|---|---|
| **No. operators** | 1 experienced operator |
| **Testing time range** | Minutes |
| **Accuracy** | Good correlation with NDG. Frequency response affected by grain size and grain-size distribution *(6)* |
| **Portability** | Better than NDG |
| **Calibration** | Material-specific calibration before every use *(1)*. Equipment calibration once a year. |
| **Approx. price** | $10,000 *(1)* |

**Moisture Density Indicator:** The moisture density indicator (MDI) uses time-domain reflectometry to estimate the density and moisture content of compacted unbound aggregate layers. The device uses an electromagnetic wave pulse as stimulus. Four electrodes are driven into the ground. Three of them form the tips of an equilateral triangle, and the remaining electrode is driven at the center. This configuration is intended to imitate the workings of a coaxial cable where the center electrode is analogous to the central conductor, the three peripheral electrodes are the shield, and the soil in between is the insulator. As the voltage pulse is transmitted to the ground, its reflection is picked up by the electrodes. The velocity of the wave generated by the pulse is related to the soil dielectric properties, and its attenuation is a function of the electrical conductivity of the soil *(7)*. Data collected by the device is used to estimate density and moisture content using proprietary software. The main limitations of this device are associated with the discrepancies between dry density measured when compared to NDG test results *(8,9)*, and the sensitivity to temperature (Table 2). Temperature effects increase when the field test temperature differs from the laboratory material calibration *(10)*. Finally, the test cannot be used in all soils *(7)*.

**Table 2. Moisture density indicator summary.**

| | |
|---|---|
| **No. operators** | 1 experienced operator |
| **Testing time range** | Setup and removal time can be considerable 15~30 min *(8)* |
| **Accuracy** | Sensitive to temperature *(7)*. Accurate moisture content measurements *(8,10)*. Dry densities differ from NDG *(8)*. |
| **Portability** | Similar to NDG |
| **Calibration** | Material-specific calibration before every use. |
| **Approx. price** | $6,000 *(1)* |

**Electrical Density Gauge:** The electrical density gauge (EDG) uses electromagnetic stimuli in the higher end of the radio-frequency range. Four 6-inch (15.2-cm) long electrodes are driven into the soil to transfer the electromagnetic signal and measure the material response. The device analyzes the recovered signals to determine the dielectric properties of the soil, which can then be used to estimate density and moisture content via material specific calibration models *(1)*. The calibration model is developed from taking material specific laboratory measurements (Table 3). However, calibration is complex and time-consuming *(5)*. The limitations of the device are associated with the high sensitivity of the results to material calibration, complexity of the calibration process, and complexity of the field measurement *(5,8,11)*. In addition to the installation, the test requires switching of connectors to and from different probes, which can be cumbersome and time-consuming *(1)*. Lastly, the average errors on the EDG determinations of density and moisture content are high compared to the NDG *(12)*.

**Table 3. Electrical density gauge summary.**

| | |
|---|---|
| **No. operators** | 1 experienced operator |
| **Testing time range** | Setup, removal and testing time can be considerable |
| **Accuracy** | Strongly dependent on material calibration *(5)*. Less accurate than NDG *(12)*. |
| **Portability** | Needs assembly of multiple components that could be lost in transit. |
| **Calibration** | Complex material specific calibration before every use. |
| **Approx. price** | $11,550 (including the calibration verifier) *(1)* |

In general, electrical methods can be used to determine density and moisture content provided they are well calibrated to the specific material for which they will be used. However, deviations in materials and environmental conditions can affect the accuracy of the test. In such case, a knowledgeable operator is needed to recognize the problem and apply the necessary corrections. However, electrical measurements are based on complex interactions between the electromagnetic stimulus and the material, and it is not clear if the average technician would have the educational background and/or experience to effectively troubleshoot the devices in the field.

### *5.2.2. Mechanical Methods*

Mechanical methods in the laboratory are the standard for determination of mechanical parameters in granular material. Load-controlled and deformation-controlled uniaxial and triaxial loadings are used to determine shear strength, stiffness, and evolution of void ratio (density) under load. All other methods (i.e., electrical and thermal) are calibrated against laboratory mechanical testing. However, in the field it is significantly more difficult to control the load transfer and boundary conditions. Therefore, the determination of mechanical properties in-situ is not as straightforward as in the laboratory. Available in-situ testing devices make use of static and dynamic plate loading, impact behavior, and elastic wave propagation phenomena.

**Soil Stiffness Gauge:** The soil stiffness gauge (SSG) was developed jointly by the Federal Highway Administration (FHWA) and the U.S. Department of Defense's Research Programs Administration in an effort to repurpose military technology originally developed for locating buried landmines into a civilian application. The target was to develop a faster, cheaper, and more accurate non-nuclear compaction testing device *(13)*. The SSG is the dynamic equivalent to a plate load test. A known force is applied to the soil via a plate or ring causing a deflection at the interface between the soil and the plate. The magnitude of the deformation is proportional to the plate geometry and the mechanical properties of the soil, i.e., modulus and Poison's ratio *(13)*. Unique to the SSG is the use of military-developed technology for the accurate determination of very small deformations that allows the use of small input loads and helps maintain the device under 25 lb (11.3 kg) for portability. The input dynamic load generated by the device has an estimated amplitude of 9 N and the test is conducted at 25 steady frequencies between 100 and 196 Hz *(14)*. Stiffness measurements are recovered from each frequency sweep and the average is reported. A single test lasts less than two minutes. The coefficient of variation for SSG measurements is less than 10% *(15)*, and its precision in fine-grained and coarse-grained soils is reported to be less than 2% and 5% respectively *(1)*. The main limitations of the SSG are related to the depth of influence. While the zone of influence of the device extends up to 10 in (25.4 cm) *(14)*, the measurement is biased by the stiffness of the upper 2 in (5.1 cm) *(16,17)*. Since the device requires a flat leveled surface, often prepared using leveling sand, the preparation procedure can significantly affect the SSG measurements *(16,18)*. The device cannot measure density and moisture content directly, but rather uses empirical correlations to estimate these parameters *(19)* (Table 4). Thus, density and moisture content values obtained from SSG are only as good as the correlation used to determine them. The development of appropriate correlations requires considerable material-specific testing.

**Table 4. Soil stiffness gauge summary.**

| | |
|---|---|
| **No. operators** | 1 |
| **Testing time range** | minutes |
| **Accuracy** | COV < 10% |
| **Portability** | Better than NDG |
| **Calibration** | Material specific calibrations are required to estimate density and moisture content *(19)*. |
| **Approx. price** | $5,500 *(1)* |

**Briaud Compaction Device:** The Briaud Compaction Device (BCD) consists of an instrumented flexible load plate, a load cell, and a data acquisition and processing unit. The mechanical stimulus is provided by the operator when leaning over the unit. The load cell allows the unit to determine the precise load applied, so the test measurements are not biased by the operator. Strain gauges in the flexible plate are used to measure deformations in the flexible plate, which are a function of the applied load and the relative stiffness between the plate and the material beneath it *(20)*. The BCD is a single piece light-weight device, which is easy to move between testing sites (Table 5). However, it can only be used in soils with moduli in the range of 5 to 150 MPa. Finally, the device does not have the capability to measure density and moisture content.

**Table 5. Briaud compaction device summary.**

| | |
|---|---|
| **No. operators** | 1 |
| **Testing time range** | seconds |
| **Accuracy** | COV < 4%* |
| **Portability** | Better than NDG |
| **Calibration** | N/A |
| **Approx. price** | N/A |

*Based on a limited number of studies *(21)*.

**Light Weight Deflectometer:** The light weight deflectometer (LWD) is a portable version of the falling weight deflectometer (FWD). The device consists of a falling mass and a rigid load transfer plate. Displacement, velocity, and/or acceleration sensors are located at the center of the loading plate. The falling mass serves as the mechanical stimulus that upon impact transfers its kinetic energy to the plate-ground system. The central deflection of the loading plate is determined and used to back-calculate the modulus of the material assuming the behavior to be analogous to the response of a constant load on a homogeneous half-space, i.e., the Boussinesq closed form solution. There are multiple versions of the LWD, each one having a different mass, sensor type and position, as well as loading plate diameter, thickness, and stiffness *(1)*. This results in a wide range of performance, particularly under certain combination of devices and soil types. Covariance can be as low as 2.1% and as high as 77.3% *(11,22)*. The influence depth of the test extends to about the diameter of the load transfer plate *(23-24)*, yet as in other surface loading tests, the measurements are biased by the stiffness of the material close to the surface. The primary limitation of the device is its high variability and poor repeatability across devices *(1)* (Table 6).

**Table 6. Light weight deflectometer summary.**

| | |
|---|---|
| **No. operators** | 1 |
| **Testing time range** | minutes |
| **Accuracy** | 2.1% < COV < 77.3% |
| **Portability** | Better than NDG |
| **Calibration** | Device specific |
| **Approx. price** | \$5,000 ~ \$10,000 |

**Clegg Hammer:** The Clegg hammer (CH) uses the impact of a free-falling weight as the stimulus to estimate the stiffness of the ground. It consists of a 'hammer' housed inside a vertical guide tube *(1)*. When the hammer is dropped, it gains kinetic energy and transfers part of it into the ground upon impact. Sensors within the hammer are used to measure the change in acceleration of the free-falling mass upon impact. The test requires using the same hammer with the same drop height in each test, thus, ensuring that the initial potential energy of the hammer remains constant. The measured change in acceleration of the hammer depends on the relative amount of energy absorbed by the soil. A stiff material would absorb less energy than a softer material. Hence, this information can be used to estimate the stiffness of the soil. The test is conducted multiple times at nearby locations. The Clegg Impact Value (CIV) is the largest deceleration recorded for four drops of the hammer *(25)*. This parameter is used to determine the Clegg Hammer Modulus (CHM), which can then be used to estimate elastic moduli of the soil *(26)*. There is a standard test procedure associated with the device: ASTM D5874. Calibration tests can be conducted to establish material-specific correlations between CIV and density *(1)* (Table 7). However, boundary effects associated with testing in Proctor molds make it difficult to recover reliable correlations.

**Table 7. Clegg hammer summary.**

| | |
|---|---|
| **No. operators** | 1 |
| **Testing time range** | minutes |
| **Accuracy** | 4% < COV < 20% |
| **Portability** | Heavier than NDG. Some models require dollies. |
| **Calibration** | Material-specific calibrations are required to estimate density and moisture content |
| **Approx. price** | \$2,500 *(27)* |

**Dynamic Cone Penetrometer:** The Dynamic Cone Penetrometer (DCP) is a field instrument used to assess the in-situ strength of unbound aggregate materials. The use of dynamic cones during the 1970's by the Transvaal Roads Department in South Africa led to the modern equipment design that began to be gradually adopted by other nations in the 1980's *(28)*.

Pioneering the use of the DCP test in the U.S. has been headed by the State Departments of Transportation of California, Florida, Illinois, Minnesota, Kansas, Mississippi, and Texas, primarily for site characterization of aggregate bases and subgrade soils *(29)*. The DCP test can be of great assistance in preliminary soil surveys, allowing road designers to rapidly identify areas of weak materials. Depth-averaged penetration rates can be used as an index to delineate the presence of weak soil layers, which can be potential candidates for stabilization *(30)*. The DCP test results are reported in terms of the penetration rate (PR), which can be used to estimate the California bearing ratio (CBR) and soil support values (SSV). The most commonly available correlations are in terms of CBR versus PR, and almost invariably show linear dependence between these two values in the logarithmic scale (Table 8). However, these correlations do not take into account any of the soil properties that define the behavior of granular materials (i.e., moisture content, particle size, particle shape, void ratio, friction angle, etc.). Furthermore, the correlations attempt to compare soil behavior that occurs under different strain regimes; CBR measures soil performance in the elastic regime, and in DCP test the probe is driven until soil failure *(31)*. To avoid obtaining misleading results, it is preferable to analyze the DCP test results in terms of penetration rate alone. Thus, the test offers only a strength index and cannot be used to accurately extract density, moisture content, strength, or stiffness.

**Table 8. Dynamic cone penetrometer summary.**

| | |
|---|---|
| **No. operators** | 2 |
| **Testing time range** | minutes |
| **Accuracy** | 2.9% < COV < 68% *(11,32)* |
| **Portability** | Similar to NDG |
| **Calibration** | Requires material-specific calibrations |
| **Approx. price** | $1,000 *(27)* |

**Portable Seismic Property Analyzer:** The Portable Seismic Property Analyzer (PSPA) is a miniature version of the seismic pavement analyzer (SPA). Both devices were developed at the University of Texas at El Paso for the characterization of pavement structures. The device consists of an elastic wave source and two receivers (accelerometers) housed in a portable device. The device is operated by a laptop computer. The PSPA measures the linear elastic modulus of a compacted aggregate layer based on the velocity and attenuation of mechanical waves *(33)*. The method of analysis is known as ultrasonic surface wave (USW) method, which shares similarities with the well-known geophysical spectral analysis of surface waves (SASW). The PSPA is a small, easy to handle device; however, it requires a laptop for data logging and reduction. The main disadvantage of the device is the need for a skilled, experienced operator (Table 9).

**Table 9. Portable seismic property analyzer summary.**

| | |
|---|---|
| **No. operators** | 1 experienced operator |
| **Testing time range** | minutes |
| **Accuracy** | 6% < COV < 18.5% *(11)* |
| **Portability** | Better than NDG |
| **Calibration** | Material-specific calibrations are required to estimate density and moisture content |
| **Approx. price** | \$20,000 ~ \$30,000 *(1)* |

The CH, DCP, SSG, and LWD have been evaluated by multiple transportation agencies for construction monitoring and quality control. Only the LWD and the DCP have been adopted, to an extent, to complement NDG in construction monitoring *(1)*. The SSG ranked the lowest in satisfaction for Departments of Transportation familiar with the device *(33)*. The PSPA is the only device that can provide stiffness measurements that are not biased by the properties of the material closer to the surface. However, very few transportation agencies have evaluated the PSPA in part due to its perceived complexity and need for skilled personnel. All of the devices presented in this section are incompatible with the needs of the state of New Mexico because none can provide reliable measurements of density and moisture content. While some device manufacturers may claim that density can be estimated using correlations, these are material-specific. Therefore, the devices would require extensive calibration and may still be too sensitive to small changes in material properties and conditions in the field to provide reliable results.

### *5.2.3. Thermal Methods*

Thermal methods in the laboratory are the primary means for the determination of moisture content. Heat is injected into wet aggregates causing the removal of water by evaporation at temperatures close to 100 °C. Since the temperatures are far below the melting point of the aggregate particles, there are no permanent changes in their properties, and the gravimetric moisture content can be easily determined by weighting the aggregates before and after oven-drying. However, the use of ovens in the field is impractical due to portability of the ovens and of the generators required to power them. Furthermore, the time required for drying and homogenization is prohibitively long for in-situ testing. The following devices have been developed to overcome these limitations.

**Speedy Moisture Tester:** This device determines the moisture content of unbound aggregates indirectly by measuring the amount of gas released in a controlled chemical reaction. Roughly 20 g of aggregates are mixed with a similar mass of a reactant (calcium carbide) inside a pressure vessel. Steel balls are added, and the container is sealed. The test continues following alternating periods of shaking (10 sec) and resting (20 sec) for 1 to 3 min, depending on the soil type. When the reaction has ended, the vessel is weighted, and the internal pressure is recorded. The two measurements are used to determine the moisture content. The main limitation of the device is the small sample size used, which can lead to inaccurate results when testing coarse-grained soils.

**Moisture Analyzer:** This device consists of a small scale equipped with an overhead ceramic heating element. The device is in essence a portable miniature oven and works in the same manner as the laboratory tests. A sample of soil is placed in a small aluminum dish and positioned inside the heating unit. The initial (wet) mass is recorded. The heating element is powered, and the mass in the scale is continuously monitored until a constant value is reached, i.e., dry mass. The mass difference and the dry mass are then used to determine the gravimetric moisture content. Moisture analyzer results have been found to underestimate moisture content. Furthermore, the small size of the device cannot accommodate particles larger than 25.4 mm (1 inch).

In addition to these devices, field microwave ovens have also been effectively used to determine the gravimetric moisture content *(6)*. Thermal devices have so far only been used in the determination of moisture content and can only partially satisfy the information needed for construction quality control.

## 5.3. Novel Thermo-Mechanical Coupling

The thermal conductivity of dry granular media is affected by mineralogy, particle size, particle packing structure, porosity, gradation, effective stress, and the presence or absence of cementation *(34-44)*. Despite the extensive body of knowledge available, universal thermal conductivity predicting models have proven elusive. The most commonly used mixing models (i.e., porosity-based models) fail to capture the effects of stresses and cementation *(42,45-47)*. Some of the previous work by Dr. Cortes and his research group at New Mexico State University on engineered thermal properties of geomaterials led to the development of a correlation between the thermal conductivity of Ottawa sand and its p-wave velocity *(48)*. A similar correlation was also observed in electrically conductive lead shot, which suggested that the contribution of electron-heat conduction to the thermal conductivity of granular electrically conductive materials was negligible. The results led Dr. Cortes to hypothesize that there is a unique pathway for heat conduction in granular media i.e., phonon-heat conduction *(48)*. However, it has been observed that the effective thermal conductivity of granular mixtures of glass beads and metallic particles increases with the metallic particle fraction *(49,50)*. To reconcile the seemingly contradicting observations, tests were conducted to determine the effective thermal conductivity, electrical conductivity and p-wave velocity of granular mixtures containing lead particles and Ottawa sand subjected to monotonic $K_o$ loading. The role of particle shape in the high thermal conductivity admixture was explored through the use of lead shot (spherical particles) and lead wire (cylindrical particles).

### *5.3.1. Materials*

The materials used in the mixtures studied were granular lead shot, lead wire, and Ottawa sand (silica). Ottawa sand and lead shot can be characterized as rounded, spherical, and uniformly graded with a mean particle size of 0.6 mm for Ottawa sand and 1 mm for lead shot. The lead wires used were solid cylindrical particles, 10 mm in length and 3 mm in diameter. In addition to the obvious differences in mechanical, thermal, and electrical material properties between lead and silica, lead particles exhibit creep under compressive stresses. Thus, the shape of lead particles changes over time under confining stress causing them to become progressively more angular. The shape and size of Ottawa sand particles remain unaltered for the range of stresses applied during this testing program.

### *5.3.2. Specimen Preparation*

Dry mixtures were poured into a cylindrical aluminum cell (152.4 mm of internal diameter and 63.5 mm of height) at preselected volume fractions of solid lead ($f_{pb}$). When the mixture reached a height of roughly 20 mm, four sensors were placed in the cell. The sensors included a thermal needle probe, a cylindrical copper electrode, and a pair of piezoelectric crystals. As more material was added, these become embedded. Once the cell was full, a cap was placed over the material to allow for vertical loads to be applied. Cables for the embedded sensors were fed through orifices present in the loading cap and were connected to the peripheral electronics. With no effort to compact the specimen, it can be assumed that its initial porosity was close to the maximum void ratio ($e_{max}$). The thermal conductivity ($\lambda_T$) was measured using a thermal needle probe (30 mm in length and 1.3 mm in diameter, East 30 Sensors) following the method introduced by Von and Maxwell *(51)*. Power for the thermal needle probe was provided by a DC power supply (Agilent E3601A), while the temperature was monitored and stored using a data logger (Agilent 34972A) at a sampling frequency of 1 Hz. The pair of piezoelectric sensors were used as source and receiver of mechanical waves. The source sensor was connected to the signal generator output of an Agilent DSO-X-2004A digital oscilloscope. The signal used was an impulse (10 μsec width and 5-volt amplitude) with a frequency below 100 Hz. Triggering occurred internally once the signal was emitted. The instrumented cell used is depicted in Figure 1.

### *5.3.3. Test Procedure*

The testing protocol mimics the steps proposed by Nasirian et al. *(48)*. The first measurement made is the p-wave velocity ($v_p$). A thermal conductivity ($\lambda_T$) measurement is conducted immediately after using a 2-volt DC input, which translates into a temperature change of 3 to 4 degrees K within the needle. The transient thermal response to the input power is recorded once per second, for 100 seconds. At the same time, the electrical resistance between the copper electrode and the perimeter of the cell is monitored for the same 100 seconds. The temperature and electrical resistance data are later used to determine the thermal ($\lambda_T$) and electrical ($\sigma_e$) conductivities respectively. The first stress increment is applied after 10 minutes, and measurements of $v_p$, $\lambda_T$ and $\sigma_e$ are collected immediately after loading, and every 10 minutes thereafter for 30 minutes. After that, the next stress increment is applied. Measurements conducted in subsequent stress increments follow the same protocol established for the first load application.

### *5.3.4. Test Results*

The effective thermal conductivity, p-wave velocity and electrical conductivity of the granular mixtures as functions of time and vertical stress are shown in Figure 2 for lead shot-silica mixtures and in Figure 3 for lead wire-silica mixtures. The addition of lead particles, either spheres or wires, results in an increase in the effective thermal conductivity of the sand-lead mixtures. The p-wave velocity of the mixtures increases slightly with the addition of lead particles reaching a maximum value at a volumetric fraction of lead of 100%. The electrical conductivity also increases with the fraction of lead particles; however, the equipment used is only capable of measuring the electrical conductivity of mixtures containing 40% or more lead particles. Thus, the percolation threshold for electrical conductivity is between 20% and 40%. Creep behavior is evident in the response of mixtures containing over 40% lead by volume (in terms of $\lambda_T$ and $v_p$).

Changes in density, inferred from vertical displacements, are combined with p-wave velocity measurements to compute the small-strain constrained modulus (*M*) according to:

$$M = \rho \cdot \mathrm{v_p}^2 \qquad [1]$$

where:
*M* = small-strain constrained modulus,
$\rho$ = bulk density, and
$v_p$ = p-wave velocity.

The results are plotted against the thermal conductivity measurements in Figure 4. The data show a remarkable linear correlation between the thermal conductivity and the small-strain constrained modulus.

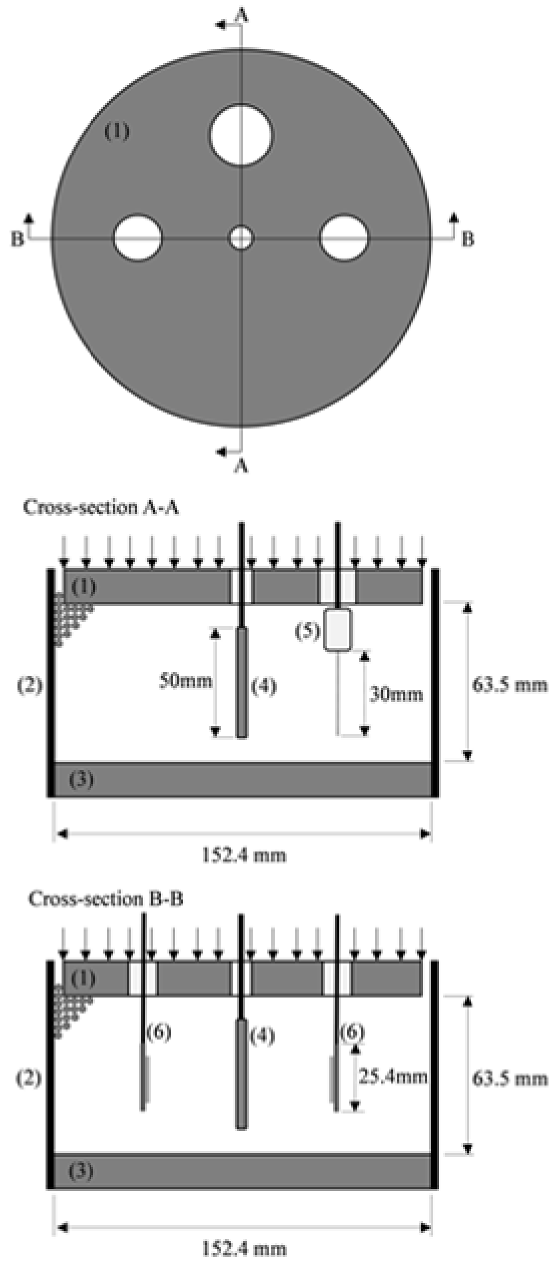


**Figure 1. Cell instrumentation: (1) electrically insulated cap, (2) electrically conductive cell, (3) electrically insulated base, (4) copper electrode, (5) thermal needle probe, and (6) piezoelectric sensors *(48)*.**

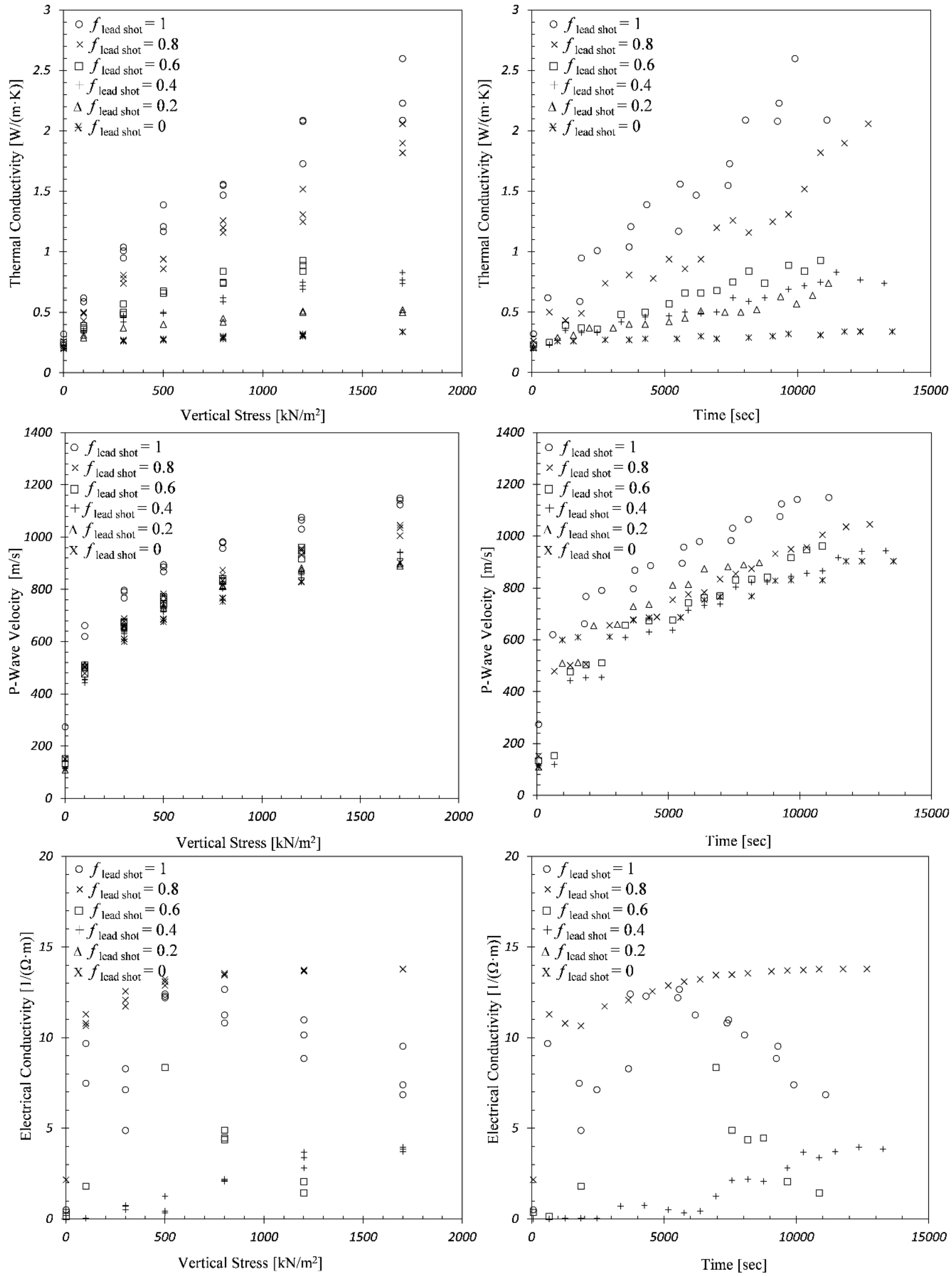


**Figure 2. Measured thermal conductivity, p-wave velocity, and electrical conductivity as functions of vertical stress (left column) and time (right column) for dry granular mixtures of Ottawa sand and lead shot subjected to monotonic $K_o$ loading.**

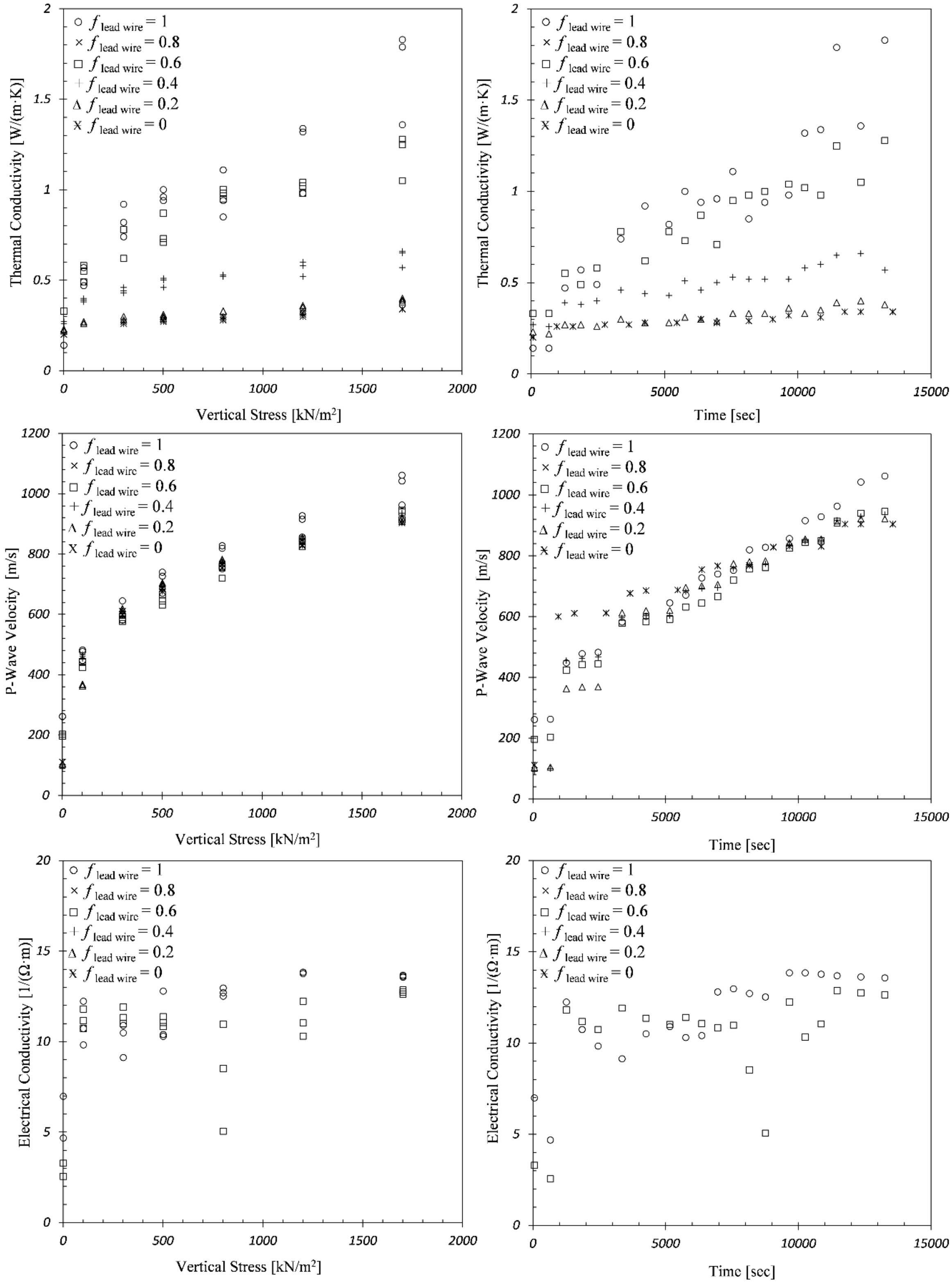


**Figure 3. Measured thermal conductivity, p-wave velocity, and electrical conductivity as functions of vertical stress (left column) and time (right column) for dry granular mixtures of Ottawa sand and lead wire subjected to monotonic $K_o$ loading.**

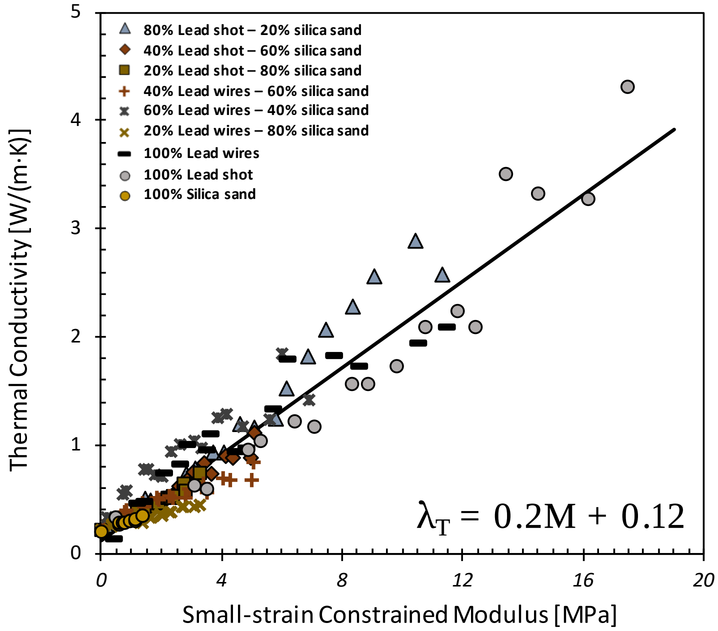


**Figure 4. Thermal conductivity ($\lambda_T$) and small-strain constrained modulus (M) of lead shot, lead wire, silica sand, and granular mixtures thereof subjected to monotonic $K_o$ loading.**

Even though the behavior of these two particulates and their mixtures cannot be taken as representative of all granular media, the strong correlation observed for such distinct materials is intriguing. Lead is a visco-elasto-plastic metal with a specific gravity of 11.3, whereas Ottawa sand particles are elasto-plastic non-conductive silica with a specific gravity of 2.7. The contrast in material properties creates the suspicion that the correlation may not be simply coincidental. Furthermore, the potential implications of a coupling between thermal conductivity and stiffness in granular media are far-reaching.

# 6. CONCLUSIONS

The successful implementation of a non-nuclear, in-situ, mechanical performance evaluation test device requires satisfying the current information needs of practice in a system-wide context. Unavoidably, the device must be able to provide reliable density and moisture content measurements to fit within the established construction control regulatory framework. A non-nuclear device that measures density and moisture content accurately, rapidly and robustly and that can be as portable as an NDG will still face some institutional inertia related to the lack of familiarity by technicians and contractors, but would be the most likely candidate to replace the NDG. However, limiting such device to the determination of these two parameters will do nothing to advance the state of the practice regarding the in-situ mechanical characterization of compacted aggregates. Thus, the real need lies in the development of a transitional device that can measure density, moisture content, strength, and stiffness.

Devices that use electromagnetic stimuli to characterize compacted unbound aggregates are primarily used to determine density and moisture content. Conversely, devices that use a mechanical stimulus are used to determine strength and stiffness. Available devices that use thermal stimulus are only used to determine moisture content. While some devices claim to provide density, moisture content, strength, and stiffness measurements, these are obtained through the use of empirical correlations between these parameters. Extensive material-specific laboratory calibration is required to obtain the correlations necessary to estimate all parameters. Yet, sensitivity to small variations in material characteristics and/or environmental conditions could render the correlations invalid when testing in the field. Therefore, none of the devices reviewed as part of this study meets all of the requirements necessary to satisfy the needs of practitioners and to narrow the gap with the state of the art.

## 7. RECOMMENDATIONS

Research efforts should concentrate in the development of a transitional device capable of measuring directly the density, moisture content, strength, and stiffness of compacted aggregates. By providing side-by-side measurements of all properties, such a device could adapt to the current construction specifications without requiring changes to the business as usual. Inspectors and contractors would have access to real-time density and moisture content data in the field, so that they can still be able to use the pass-fail criteria they are familiar with, and strength and stiffness data can also be recorded and made available to engineers and designers. Over time, the compiled data set could be used to develop progressive modifications to the regulatory framework, effectively phasing out density and moisture content evaluation criteria in favor of mechanical performance standards.

The development of such a device cannot rely on the use of a single stimulus but could draw from electromagnetic, thermal, and mechanical methods, and combine them into a self-contained portable device capable of directly measuring all parameters of interest. Of particular interest would be the development of a device that could take advantage of the thermo-mechanical coupling discussed in section 3 of this report. Since no single device can be improved beyond its inherent physical limitations, automation alone cannot solve the problem. However, automation can, and needs, to be central to the development of any new device to minimize the need for operator input and optimize its performance under typical field conditions.

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