NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **103**

RAPID TEST METHODS FOR FIELD CONTROL OF HIGHWAY CONSTRUCTION

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **103**

RAPID TEST METHODS FOR FIELD CONTROL OF HIGHWAY CONSTRUCTION

J. D. ANTRIM, F. B. BROWN, H. W. BUSCHING,
J. A. CHISMAN, J. H. MOORE, J. P. ROSTRON,
AND A. E. SCHWARTZ
CLEMSON UNIVERSITY
CLEMSON, SOUTH CAROLINA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE FEDERAL HIGHWAY ADMINISTRATION

SUBJECT CLASSIFICATIONS

- BITUMINOUS MATERIALS AND MIXES
- CONSTRUCTION
- MINERAL AGGREGATES
- FOUNDATIONS (SOILS)

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1970

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn, it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP Report 103

Project 10-4 FY '64 & '65
ISBN 0-309-01891-9
L C Card No 70-607814

Price: $5.00

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the Federal Highway Administration Individual fiscal agreements are executed annually by the Academy-Research Council, the Federal Highway Administration, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, nor of the individual states participating in the program

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

(See last pages for list of published titles and prices)

FOREWORD

By Staff
Highway Research Board

The suitability of acceptance procedures for assuring adequate quality of construction continues to be of concern to highway agencies. Although the research reported herein does not resolve all problems in the field of quality assurance, it does provide an over-all review of the problem and proposes several techniques and innovations that should be of value to those responsible for acceptance testing programs. It also contains an extensive annotated bibliography on rapid test methods for highway construction. Materials, testing, and construction engineers should find the publication useful, particularly from the standpoint of providing young engineers and technicians with a view of current testing practice in the highway field. The report should also be useful in establishing priorities for future research, both at the individual state and the national level, in the field of highway materials testing.

Increasing interest and involvement of the citizenry in matters of public concern—such as the planning, design, and construction of public works facilities—has resulted in greater attention being placed on procedures for assuring proper control over the expenditure of public funds. Physical documentation of materials quality and construction performance is necessary—the inspectors' experience and judgment as a basis for acceptance or rejection of an item is no longer being construed as adequate documentation. Due to the inherent variability of many highway construction items, the increasing use of statistical concepts in acceptance programs is inevitable. These factors, plus the demands of the accelerated highway contruction program, have resulted in an increased amount of testing and, consequently, the need for improved test methods—methods that are rapid and, preferably, nondestructive.

Accordingly, the objectives of this broad, three-year, $100,000 study undertaken by the Clemson University researchers were (1) to explore and summarize current practice in the field of highway construction testing, (2) to identify the areas of greatest need for development of more rapid sampling and testing methods, and (3) to undertake a program of evaluation and development of test methods in the areas of greatest need. The research was initially divided into four categories: asphalt paving mixtures, base course construction, soil compaction, and portland cement concrete paving. Each category was further subdivided according to particular characteristics that are normally controlled or evaluated during construction. A literature survey of current practices in quality control and acceptance testing was conducted in addition to investigating literature concerning new methods for rapid field control of construction. Evaluation or further development of nuclear methods for measuring moisture and density of highway components and nondestructive methods for determining pavement thicknesses were specifically excluded from this study for the reason that they were the subjects of other NCHRP projects. To bring the study up to date with regard to ideas, opinions, and data, personal interviews were conducted with highway engineers and principal investigators of related research projects. Highway departments were visited on a regional basis and included the Northeast, South, Midwest, Southwest, and Far West.

Several facets of this report are of immediate interest to those having responsibility for acceptance testing programs. First, there is the survey of current testing practices in the highway departments, the problems encountered therein, and the subjective opinions as to which phases of construction control are in greatest need of rapid tests. The provision of this information constitutes a logical supplement to the current Highway Research Board efforts under NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," to bring together all useful information in every area of concern and make it available to the highway fraternity. Second, and more specifically, both the work associated with the evaluation of several current procedures and the attempts to develop new or improved procedures warrant careful study. Because the scope of this investigation was quite broad, ambitious, and less exhaustive than desired due to the funding and time limitations, individual highway departments may wish to further pursue the developmental accomplishments.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-4 by the Department of Civil Engineering, Clemson University, with Arnold E. Schwartz, Head of the Civil Engineering Department and Associate Professor of Civil Engineering (currently Dean of the Graduate School, Director of University Research, and Associate Professor of Civil Engineering), as Principal Investigator. The other authors were, respectively, John D Antrim, Associate Professor of Civil Engineering (currently Professor of Engineering, The Pennsylvania State University), Farrell B Brown, Associate Professor of Chemistry; Herbert W. Busching, Associate Professor of Civil Engineering (currently also Head of the Civil Engineering Department), James A. Chisman, Assistant Professor for Mechanical Engineering (currently Associate Professor of Operations Research); Joseph H. Moore, formerly Head of the Civil Engineering Department and Professor of Civil Engineering (currently Head, Engineering and Technology Division, The Pennsylvania State University); and Joseph P. Rostron, Associate Professor of Civil Engineering

Sincere appreciation is expressed to the many engineers and staff members of state highway departments, federal agencies, and research organizations for their generous cooperation in providing standard specifications, test manuals, reports, and other valuable information necessary for the initial phase studies

The assistance of the South Carolina State Highway Department and the Bureau of Public Roads, who sponsored a concurrent research program, "Rapid Means of Determining Moisture Content and Density of Soils and Granular Materials," is also gratefully acknowledged.

The facilities and equipment used in the development and evaluation studies were those of the Department of Civil Engineering, Clemson University.

RAPID TEST METHODS FOR FIELD CONTROL OF HIGHWAY CONSTRUCTION

SUMMARY

The Interstate Highway program and the increasing volume of traffic on American roads has resulted in an accelerated program of highway construction. New techniques and improved construction equipment have placed heavy demands on quality control and acceptance test procedures. Consequently, state highway personnel as well as contractors realize that faster construction control test methods are needed.

The over-all objective of this research project was to determine the state of the art in the development, need, and use of rapid test methods and to develop and evaluate new test methods for field control of construction. The project consisted of two distinct phases. In the first phase of the project, a literature survey of new rapid methods and current practices in quality control and acceptance testing was conducted. A study, using statistical methods, also was made to determine time limits for rapid tests.

A number of state highway departments and highway construction contractors returned questionnaires concerning their construction needs and current practices. Standard specifications and testing manuals were also furnished by 38 state highway departments. To bring the study up to date, personal interviews were conducted with highway engineers and principal investigators of related research projects. Fifteen state highway departments were visited on a regional basis.

The relative priority of rapid tests needed for construction control was determined from questionnaires, interviews, and the literature reviews. The priority within each area of construction and the over-all priority of each test with respect to other tests in all areas were established. It was found that the broad area of compaction control, which includes the determination of standard densities and field densities for base and earthwork construction as well as asphalt pavements, had the greatest need for rapid test methods. The determination of asphalt content also ranked high in over-all priority. Next in the order of priority were determinations of concrete strength and base course gradation.

The second phase of the study was concerned with the development and evaluation of new rapid test methods or principles which, on the basis of the findings of the initial phase, were considered to be worthy of further investigation. The development and evaluation studies were conducted in the areas of asphalt content and compaction control of bituminous pavements, gradation and compaction control of base course materials, and density and moisture content of soils.

Two methods, applicable to asphalt content determination, were evaluated; a third method was developed as a new technique. One of these chosen for evaluation was the pat-stain method in which the hot asphalt mix is compacted against a sheet of paper to form a stain imprint. The stain is visually or photoelectrically compared with a stain of a known mix to estimate the asphalt content. Although the method is rapid, it did not appear to be accurate enough to have any practical

application to construction control testing. The Wyoming flask method (a displacement-type test using kerosene as a fluid) also was evaluated and was found to be a promising rapid method for determining asphalt content. The convenience and suitability of the Wyoming flask method was evaluated and compared with a third (ignition) method of determining asphalt content that was developed as part of the second phase of the project. In the ignition method, the sample of asphalt mix is burned, in the presence of oxygen, in a special furnace The loss in weight on burning is interpreted as the weight of asphalt in the mix plus a small loss due to change in weight of the aggregate. The method was found to be rapid (requires about 30 min) and relatively accurate.

A sampling technique that uses a thermoplastic cup for easy removal of bituminous concrete density specimens was developed as a means of compaction control. Tenite polyallomer of 5-mil thickness performed well as a container that would not melt or puncture, yet became soft enough from the heat of the mix to avoid restraint of the contained mix under compaction. Also evaluated was an air permeability device that was found to be suitable for measuring changes in pavement density.

A laboratory study was conducted to determine the feasibility of using an incomplete series of sieves to estimate the gradation of several types of aggregate. A secondary portion of the study was to determine what sieves could be used most effectively in estimating the amount of degradation or segregation that resulted from compactive effort applied in the laboratory. The base material tested in this study had degradation characteristics that appeared to be predictable, and it was found that a single sieve in the area of greatest expected gradation change would be satisfactory for detecting approaching violation of gradation specifications.

Methods for determining the density of base course materials and soils also were studied. These methods used a drop-hammer penetrometer and dynamic attenuation procedures The penetrometer, developed at Clemson University, is a portable device using a 5-lb or 10-lb drop weight and a ⅝-in.-diameter bullet-shaped penetration needle to penetrate various thicknesses of base material or soil. The penetration resistance of the base or soil can be readily determined with the penetrometer by counting the number of blows required to penetrate from 2 to 6 in. and dividing the number of blows by the penetration distance. Although the penetration resistance of fine-grained materials is greatly influenced by molding water content of laboratory samples, it was found that, for a given moisture content, a linear relationship existed between dry density and the log of the penetration resistance. A graphical-mathematical calibration procedure, which takes into account the moisture content of the sample, was used to calibrate a crushed granite-gneiss base material, three A-2-4 soils, and two A-2-6 soils. The over-all standard error in predicting the dry density of these laboratory samples from penetration resistance and moisture content using calibration equations developed for these materials was 2.2 pcf. Although the calibration is complicated by the influence of moisture, the speed and accuracy of the test method encourage the use of the penetrometer for compaction control of uniform subbase and granular base material.

Experiments using ultrasonic ceramic crystal driver and pickup transducers were performed on several different soil samples compacted at various densities and moisture contents to determine the feasibility of this technique in measuring the density of soils. Coupling of the transducers to the soil was accomplished by the use of aluminum pegs, one for the driver and one for the pickup, driven into the soil a few inches apart. The transmission of vibration through the soil sample was measured in output volts of the pickup transducer when the driver was powered with a constant 60-volt signal. Although the statistical analysis of the data revealed a definite correlation between soil density and the log of the output volts at 12, 24, and 32 kc, the standard error obtained does not indicate, at present, a strong possibility of making accurate measurements of density by the application of ultrasonics. The outlook for fine-grained soils using the 12-kc test frequency is the most promising, but the 5.2-pcf standard error obtained with these soils is still too high to satisfy the requirements of construction control testing. Similar tests with dynamic attenuation which involved measuring the power input to a low-frequency Degebo (German Research Society for Soil Mechanics) vibrator placed on the surface of the soil also produced negative results.

Two rapid field methods of determining moisture content were evaluated: (1) the alcohol burning method, and (2) the calcium carbide gas pressure method. The purpose of these studies was to evaluate the accuracy of the two methods when applied to soils of high clay content. In addition, efforts were made to determine the best sample size, amount of alcohol, and number of burnings required for the alcohol burning method. With the proper procedure, both methods were sufficiently accurate for tests related to compaction control.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

OBJECTIVE

The Interstate Highway program and the increasing volume of traffic on American roads has resulted in an accelerated program of highway construction. New techniques and improved construction equipment have placed heavy demands on quality control and acceptance test procedures. Consequently, faster construction control test methods are needed as the rate of construction increases.

Revision of many state highway specifications and increasing demand for the use of statistical quality control and acceptance plans has compounded the problem by requiring a greater number of tests for a given quantity of material. McMahon (*1*) states that in the past the inspector has used engineering judgment based on his knowledge of materials and tests in accepting or rejecting an item of construction when some results are outside the specification limits. Wide variations in test results have long been known, according to Izatt (*2*), and interpreted with an equal variability by highway engineers. Hence, new rapid test methods must be developed and studied to evaluate accurately compliance with specifications.

The over-all objective of this research project was to determine the state of the art in the development, need, and use of rapid test methods and to develop and evaluate new test methods for field control of construction.

RESEARCH APPROACH

The initial phase of the project consisted of a literature survey and a review of current test practices. A second phase of the project consisted of the development and evaluation of new rapid test methods. The research initially was divided into four categories: (1) asphalt paving mixtures, (2) base course construction, (3) soil compaction, and (4) portland cement concrete paving. Each category was further subdivided according to particular characteristics that are normally controlled or evaluated during construction. A literature survey of current practices in quality control and acceptance testing was conducted in addition to an investigation of literature concerning new methods for rapid field control of construction. Because of the large number of publications consulted for the literature survey, a manual information-retrieval system patterned after that recommended by the Engineering Joint Council (*3*) was used.

As part of the study of current practice a request was submitted to each state highway department for their current specifications and testing manuals. A total of 38 states (Table 1) complied with this request. For the majority of the remaining states the specifications and manuals were either out of print or under revision. Thus, the information regarding specified test methods, although not 100 percent inclusive, is significantly representative.

To bring the study up to date, personal interviews were conducted with highway engineers and principal investigators of related research projects. Fifteen state highway departments were visited on a regional basis. In the Northeast, the Pennsylvania, New York, and New Jersey highway departments were contacted. Virginia, North Carolina, and South Carolina highway officials were visited in the South. The Midwest visits covered Kansas, Michigan, Ohio, and Kentucky. Southwestern states visited included Texas and Colorado. California, Oregon, and Washington highway agencies were interviewed in the Far West. Research agencies conducting related NCHRP projects also were contacted. To supplement information obtained from personal interviews, two questionnaires were prepared and sent to highway departments and highway construction contractors. The questionnaires requested information concerning: (1) the testing procedures used by highway departments, (2) the rate at which sampling and testing was required for construction control, (3) the approximate duration of time required to perform each type of test, (4) the average work delay, if any, caused by a particular test, and (5) subjective opinion as to which phases of construction control were in greatest need of rapid tests.

TABLE 1

INFORMATION OBTAINED FROM STATES

STATE	PERSONAL INTERVIEW	QUESTIONNAIRE FIRST	QUESTIONNAIRE SECOND	SPECS AND MANUALS
Alabama		x		x
Arizona			x	x
California	x		x	x
Colorado	x	x		x
Delaware			x	x
Florida		x		x
Georgia		x		x
Hawaii			x	x
Idaho			x	x
Illinois			x	x
Indiana			x	x
Iowa				x
Kansas	x	x		x
Kentucky	x	x		
Louisiana		x	x	x
Maryland		x		x
Michigan	x			x
Mississippi		x	x	x
Missouri		x	x	x
Montana		x		
Nebraska			x	x
Nevada			x	x
New Hampshire			x	x
New Jersey	x	x		x
New Mexico				x
New York	x	x	x	x
North Carolina	x		x	x
North Dakota		x		x
Ohio	x	x		x
Oklahoma			x	x
Oregon	x			x
Pennsylvania	x			x
South Carolina	x			x
South Dakota				x
Tennessee			x	
Texas	x			x
Utah		x	x	x
Virginia	x	x		x
Washington	x		x	x
Wisconsin		x		x
Wyoming			x	x
Total	15	18	20	38

ANALYSIS, DEVELOPMENT, AND EVALUATION OF RAPID TESTS

Materials specifications have long reflected the necessity of requiring a minimum number of tests for determining the quality of material or work to be accepted. Usually, the number of such tests was chosen arbitrarily. In some cases the number of tests was based on how much time and money were available for these tests. However, if statistics are to be applied correctly, sample selection must be free of bias; otherwise, efforts to project the attributes of the sample to the entire quantity of material will be thwarted.

Following the literature review and the personal interviews, several test procedures were selected for development and evaluation. This development and evaluation was conducted in three of the initial four categories—asphalt paving mixtures, base course construction, and soil compaction. The area of portland cement concrete paving was omitted because test methods were already being developed in other NCHRP projects in this category.

The development and evaluation of rapid test methods for the control of construction of bituminous pavements was concerned primarily with the development of an ignition method for the determination of asphalt content. A sampling technique that uses a plastic cup for easy removal of bituminous concrete density specimens was developed.

A laboratory study was conducted to determine the feasibility of using an incomplete series of sieves to estimate the gradation of several types of aggregate A secondary portion of the study was to determine what sieves could be used most effectively in estimating the amount of degradation or segregation that resulted from compactive effort applied in the laboratory.

Methods for determining the density of soils and base course materials were also studied. These methods used a penetrometer and dynamic attenuation procedures. A drop-hammer penetrometer developed at Clemson University was used in this phase of the research. The apparatus was portable and was capable of penetrating various thicknesses of base material and permitted penetration measurements to be made readily. The control of compaction by methods employing attenuation or transmission of vibrations through soil attenuation was considered to be theoretically feasible on the basis of a review of literature, and a high-frequency device was evaluated as a rapid means of determining the density of compacted soils. Emphasis was not placed on nuclear equipment for measuring density and moisture content of soils and base course materials during the second phase of the study because this was the subject of other research in the NCHRP.

In addition to the rapid test methods and devices already mentioned, other evaluations and studies pertinent to the subject were undertaken and are reported separately in the appendices. These are: (1) moisture content determination by calcium carbide gas pressure method and alcohol burning; (2) determination of soil density using a low-frequency vibration technique; (3) a field method of determining relative compaction of granular materials using a vibratory compactor; and (4) potential uses of electromagnetic waves in construction control testing. The efforts of the investigators were directed toward the exploration, development, and evaluation of new rapid techniques that might offer practical solutions to the problem of field testing for quality control of highway construction. In this search, the potential use of electromagnetic radiation as it applies to rapid and nondestructive testing of materials was explored. Emission and absorption spectroscopy as well as reflection and refraction of the dielectric interface for all regions of the spectrum were considered for use in the determination of the bulk and composite properties of soil, aggregate, and cemented materials.

CHAPTER TWO

FINDINGS OF INITIAL PHASE

CRITICAL AREAS

The relative priority of rapid tests needed for construction control was determined from questionnaires and interviews. The priority within each area of construction and the over-all priority of each test with respect to other areas are shown in Figure 1. In each case, the test or area with greatest priority is considered to be 100, and others are ranked lower by comparison with the maximum. For the case of unanimous opinion in which three tests are ranked one, two, and three in priority, the first rank attained a value of 100; the second, 50, and the third, 25. Intermediate values of priority would result from divided opinion. The embankment area of construction was the only area in which nearly unanimous opinion caused the bar graph to approach the ideal example cited.

It can be seen that in areas involving earthwork and base construction, density was the most critical by a considerable margin. Density also ranked high in the asphalt pavement area, although asphalt content ranked slightly higher. Considering over-all priority, density tests are rated first, second, fourth, and fifth, whereas asphalt content ranked third. Base gradation and concrete strength tied for sixth place, with a variety of other tests following closely. The two areas of construction that have the greatest and nearly equal over-all priority for rapid tests are base and asphalt pavement construction. Embankment tests ranked third; concrete pavement and subgrade tests were tied for the last place.

In evaluating the over-all need it appears that the broad area of compaction control, which includes the determination of standard density and field density for base and earthwork construction, has the greatest need of more rapid test methods.

LITERATURE SURVEY

One purpose of the study was to review literature concerning test methods, rapid or otherwise. The test methods have been classified as pertinent to asphalt paving mixtures, base course construction, soil compaction, and portland cement concrete paving. Within each of these four groupings the literature is reviewed with respect to various properties that are of concern. A list of articles, with abstracts, concerning rapid test methods appears in Appendix E.

Asphalt Content of Paving Mixtures

Of the tests for asphalt paving mixtures, such as stability, density, and void content, the determination of asphalt content was found to be the most critical.

Currently available methods for determining asphalt content can be generalized into three categories: extraction methods, displacement methods, and nuclear methods.

There are two basic types of extraction tests: the centrifuge type, which is covered in AASHO designation T 166 (*4*), and the reflux types, such as the Maryland extractor (*5*) and AASHO designations T 170 and T 184. The centrifuge method depends on rapid rotation of a centrifuge bowl to force clean solvent through the bituminous mixture until the discharge of clear solvent indicates that the asphalt has been removed. The reflux method depends on the solvent being vaporized by heat and then condensed so that the condensate drips through the mixture and dissolves the asphalt.

The Road Research Laboratory (Great Britain) has developed a test method known as the rapid methylene chloride method (*6, 7*). The bitumen content can be determined in 30 to 90 min by use of this method. Deter-

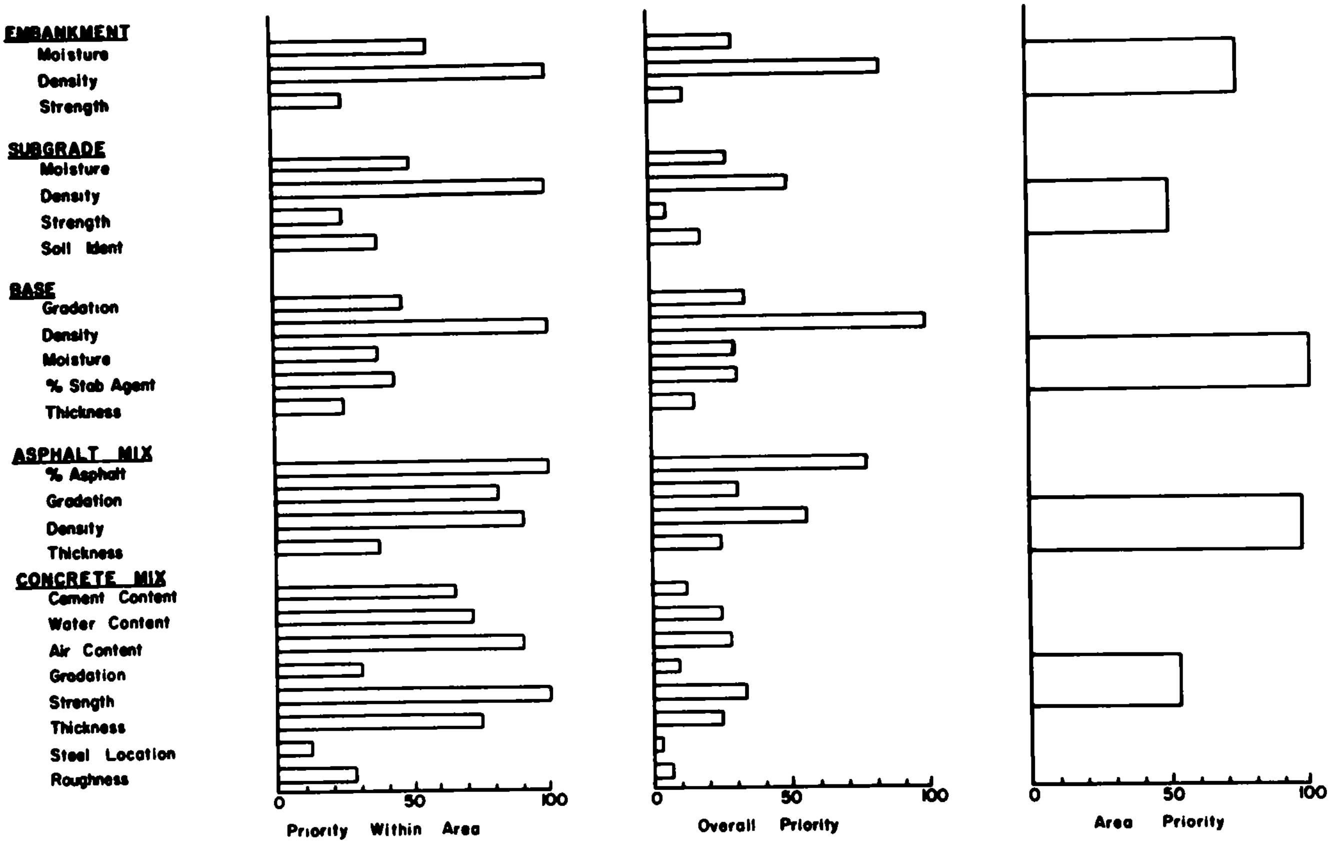


Figure 1 Relative priority of rapid tests needed for construction control

mination of the bitumen content is accomplished by placing a weighed portion of the mixture into a container along with a measured volume of methylene chloride. The specimen is shaken by a mechanical shaker and then centrifuged or filtered under pressure whereby the solvent is removed A modification of the method requires a total test time of 2 to 3 hr and uses a special sieving apparatus that permits extraction of the binder and gradation analysis of the aggregate in one operation.

Another variation of the extraction-type test is a method (*8*) developed for field use that uses vacuum filtering to decrease the test time. A sample weighing approximately 2,000 gm is tested in an apparatus that operates on a principle similar to that of a Buchner funnel. By using a vacuum under the filter, a sample can be washed clean in only four or five washes of cold methylene chloride, reducing total test time to about 45 min.

Commonly used extraction methods require considerable time and the equipment is not well suited to field installation. In addition, the sample size for the centrifuge method is smaller than may be desirable, and the solvents are toxic and/or inflammable. The rapid methylene chloride method is somewhat faster than conventional extraction methods, however, it requires special equipment, the solvent is toxic, the sample size is small, and the test procedure is complicated

A displacement-type test, known as the Wyoming flask method (*9*), is particularly suited for field use because of its simplicity. Displacement volumes of a 1,000-gm sample of the aggregate blend and a 1,000-gm sample of the mixture are determined in a 1,000-ml Chapman-type flask (stem diameter of 2.5 cm) with kerosene as the fluid. The asphalt content is then determined by the application of Archimedes principle. The complete test is normally performed in 40 to 60 min, depending on the operator, temperature of the mix, and type of mix. The Wyoming flask method uses a sample that may be smaller than desirable, however, the test procedure is simple and fast, and it has the added advantage that, when the aggregate type and blend of a plant mixture is under control, the volume displacement determination of the aggregate can be omitted after a few initial determinations. Elimination of aggregate volume reduces the duration of the test from 20 to 30 min.

One solventless method for determining asphalt content is the pressure-volume method (*10*) that uses a modified Washington air meter. The solid volume of the mixture is obtained by measuring the bulk volume of the mixture (by water displacement) and then deducting the volume of voids that was measured by the air meter. Asphalt content can be calculated by using known specific gravities of the materials, or it may be read directly from a calibration curve. Although the pressure-volume method does away with toxic solvents it requires the establishment of a calibration curve for each mixture and a bulk volume determination for each sample tested.

Nuclear methods for determining asphalt content are under development and so far their use has been limited to controlled research programs (*11, 12, 13, 14, 15*). Determination of asphalt content is possible because the hydrogen content of asphalt causes thermalization of the neutrons Walters (*12*) has developed a procedure that permits determination of asphalt content of a sample of the uncompacted mixture (13 to 15 lb) in approximately 20 min. The nuclear method is potentially a rapid test method Some disadvantages of the method are that it requires the establishment of a calibration curve each time a material is changed, and the instruments used are expensive and delicate

A test method known as the pat-stain test has been described by Richardson (*16*), and a recent variation of the test method is described by Smith (*17*). The test (and variations of it) provides for the determination of asphalt content by visually comparing the stain on paper of the unknown mixture with the stain of a mixture of known asphalt content. The pat-stain test is simple to perform, but it is not very satisfactory when applied to currently used asphaltic concrete paving mixtures.

Stability of Asphaltic Paving Mixtures

Stability testing of bituminous mixtures is more commonly associated with mixture design; hence, when field control tests are performed, they are done with equipment that is used in the mixture design procedure.

There are various test methods in existence (*18*). Two widely used methods, the Marshall method (*19*) and the Hveem method (*19*), permit the use of field samples of compacted mixtures. The Marshall method has had wider use in the field, because it is a simpler method and the apparatus can be carried into the field without undue difficulties

Chu and Spangler (*20*) developed a stability test that requires the sampling of the paving mixture at the hot-mix plant and then uses a single mold for both molding and testing. A semi-confined compression test is performed while the mixture is still hot; the time from molding of the specimen to completion of testing is approximately 10 min This stability test was the only field test method for stability found in the literature search Although this test method is fast, the conditions imposed during molding and testing require that the test results be related to the mix design method being used.

Use of the mix design test procedures has the advantage of eliminating correlation work, but only if the preparation and testing of the test specimen follow the established laboratory procedure.

Bulk Density of Asphaltic Paving Mixtures

The bulk density of compacted mixtures is normally determined by a water-immersion method, AASHO designation T 166. Specimens are obtained from the pavement by cutting, by coring, or by the aid of devices such as metal rings and paper cups

The Ohio Highway Department developed an apparatus known as a volumeter (*21, 22*) The volumeter has two chambers. Initially, air pressure in the sample chamber is raised to the operating pressure This pressure is then allowed to dissipate into a second chamber. A calibration curve is used to relate the equalization pressure to the specimen volume. Entrance of air into the specimen during the test is prevented by enclosing the specimen in a rubber membrane. Volume determinations by the volumeter are not difficult and require approximately 5 min to perform.

The nuclear method (*15, 23, 24, 25*) is a recently developed nondestructive test method. The nuclear density method makes use of the fact that absorption and scattering of gamma rays by a material is related to the density of the material. The nuclear method is a fairly fast test method and has the advantage of being a nondestructive, in-place type of test. However, it requires the establishment of calibration curves, and the instrument used is expensive and delicate.

Density determination by the water-immersion method or the Ohio volumeter method requires the removal of a specimen from the pavement. This removal can be a time-consuming process, especially if the specimen is to be obtained by coring. Coring, unfortunately, cannot take place until the compacted mixture has cooled, although the use of dry ice will speed up this process. The coring operation also introduces a problem in that, during the coring operation, the lubricating water is absorbed by the specimen. Use of devices such as a metal ring or a paper cup represent attempts to eliminate or reduce water absorbed during coring; however, these devices do not produce a representative sample because lateral confinement is not provided by the paper cup. Development of a container for sampling with limited lateral confinement could overcome this difficulty.

The water-immersion method permits rapid volume determination of a specimen and is simple to perform; however, specimens will absorb varying quantities of water and for porous specimens it is necessary to seal the permeable voids with paraffin or some other water sealant.

Void Content of Asphaltic Paving Mixtures

Air voids can be determined directly by pressure methods or indirectly by permeability measurements or by calculations that use various specific-gravity relationships.

Direct Measurement

Rice (*26*) conducted exploratory research on the use of a modified "Washington" portland cement concrete air meter at an operating pressure of about 29 psi and found that the best results were obtained when the specimen was vacuum-saturated prior to use of the air meter. To determine the total void volume of specimen, the volume of the absorbed water must be added to the void volume determined from the pressure test.

A high-pressure device developed in Illinois (*27*) uses an operating pressure of 5,000 psi to measure the air void volume directly. After the specimen is placed in a container, the surrounding air is replaced by water and then the pressure is applied through a system that is actuated by a hydraulic hand pump. Experience has shown that satisfactory results are obtained when the aggregate particles are completely coated with asphalt and the aggregate has a low absorption in the case of pavement cores. In all cases, 48 hr of soaking in water prior to conducting the pressure test was found necessary because specimens absorbed water rapidly during the short time they were in the container prior to the application of pressure. The total volume of voids determined by this high-pressure method is also the sum of the voids measured by the pressure test plus the volume of water absorbed during the soaking period.

The pressure methods for direct measurement of void content require special equipment, and the time from removal of a specimen from the pavement to completion of the test is considerable. One disadvantage of the pressure method is that water is used to transmit pressure, thus, it is necessary to fill the permeable voids with water before performing the test. This absorbed water represents a portion of the total voids; hence, additional volume determinations are necessary to establish its magnitude.

Permeability Measurements

The permeability of bituminous pavements can be evaluated in terms of either air flow or water flow. Permeability is a function of interconnected air voids. Because these permeable voids can greatly influence the durability of the pavement, many persons consider permeability to be more important than the total air void content.

Air permeability devices have received attention over the last decade (*28, 29, 30, 31, 32*). One instrument (*33*) is commercially available and is capable of measuring the air permeability of in-place pavements at a rate of approximately 5 min per test. The test is performed by placing the apparatus on the pavement surface and maintaining a specified pressure in the apparatus, thus forcing air out of the apparatus and into the pavement. Air permeability is measured by the volume of air that leaves the apparatus in a specified time period. Another recently developed air permeability device (*34*) uses a pressure drop to draw air through the pavement into the apparatus rather than forcing the air into the pavement.

A water permeability method (*35*) that is used by the California Division of Highways (and is detailed in Test Method No. Calif. 341-A) can be performed in 3 to 5 min. Water from a calibrated container is fed into a 6-in.-diameter reservoir (formed by a ring of cup grease) over a 2-min period at a rate just sufficient to keep the pavement surface moist.

The permeability method is a rapid test method that is not difficult to perform and has the advantage of being nondestructive and can be used to test materials in-place. However, it measures only interconnected voids; hence, its value is questionable when total void content is desired.

Calculations

Air void content can be calculated from weight-volume relationships of the mixture constituents; however, a reliable method of determining the volume of asphalt absorbed by aggregate during mixing has not been developed

Considerable effort has been directed toward developing dependable methods for determining the true no-voids density of the mixture and the effective specific gravity of the aggregate. The better-known methods include: the vacuum-saturation method (*10, 36, 37*), the solvent-immersion method (*38*), the asphalt-immersion method (*39, 40*), and the excess-asphalt method (*41*).

Calculations of void content by the use of certain weight-volume relationships require considerable time because the different specific gravities must be determined first by one of several test methods. These test methods are unsatisfactory in that they do not agree on the amount of asphalt absorbed by the aggregate; hence, the calculated void contents will vary.

Density of Granular Base Materials

Fox and Page-Hanify (*42*) have outlined the development of methods for determining the bulk density of soil. Attempts to develop a satisfactory method for determining soil density were recorded as early as 1908 (*43*). By 1918, Israelson (*44*) devised the sand replacement method for determining hole volume. Beckett (*46*) in 1928 used viscous fluids for replacement of the excavated soil, and later Veihmeyer (*47*) recommended the use of sampling tubes to remove a measurable volume of soil.

Because these early sampling and measuring devices were designed primarily for agricultural soil testing they were not readily useful for crushed stone and soil aggregate mixtures without modification. Rock fragments or gravel usually prevent the use of sampling tubes, and high porosity of granular materials discourages the use of the viscous fluid method. Development of test methods for granular materials has, therefore, been directed toward the water-balloon apparatus and the sand replacement method.

Humphres (*48*) notes that early water-balloon devices were unsatisfactory because, for low-porosity material, air was trapped at the bottom of the hole and balloons were usually too stiff to fill completely all the voids around the perimeter of a hole in clean, coarse-grained material. He also states that the sand replacement methods are subject to external influences, such as vibrations, humidity, and surface irregularities (*49*).

Many devices designed primarily for use in fine-grained soils are not suited to fragmented, granular material because of the small volume that they measure. The sample size required increases as grain size is increased in order to maintain sufficient accuracy. A sample size of 3 to 5 lb may be satisfactory for fine-grained soils, whereas a 15-lb sample is required for aggregate with a 2-in. maximum size (*45*). An extrapolation of this criterion indicates that a 40-lb sample would be required for 4-in. maximum size aggregate. Thus, for the general case, a minimum hole volume of about 0.1 cu ft is required for base course material; larger aggregates may require up to 0.5 cu ft.

Both California and Washington have developed methods that use large samples for density determination. All of these procedures are specification methods and are in current use by these states. The California method (*51*) is essentially a large sand-cone apparatus and involves replacing the excavated material with a known weight of calibrated sand. A minimum hole volume of 0.15 cu ft is specified by the California method; however, larger holes up to 0.25 cu ft can be used. The Washington apparatus (called the densometer) can measure hole volumes up to 0.5 cu ft and 20 in. deep (*52*) According to Humphres (*48*), a two-man team can perform 30 tests in an 8-hr period in crushed-stone base course material.

Another water-balloon device, the Rainhart volumeter (*53*), can be used to measure density in granular material accurately. The largest model volumeter can measure hole volumes up to 0.14 cu ft; thus, it is suitable for measuring the density of aggregates normally used in base course construction.

Coffman (*54*) describes a procedure that improves both the speed and accuracy of the sand-cone apparatus. The speed is increased by eliminating the necessity of leveling the soil surface prior to testing. The error that normally would be induced by the surface roughness is compensated for by filling the void between the base plate and the soil surface with a small amount of sand prior to excavating the hole. The amount of sand needed to produce a level surface in contact with the base plate is a measure of what the test accuracy would be if the void had not been filled.

The nuclear surface density gauge that measures the density of a material by backscatter or direct transmission of gamma radiation is a promising device capable of rapidly measuring the density of compacted soil or granular base material. Nuclear moisture gauges also are available. The nuclear moisture gauge, which usually shares components with the nuclear density gauge, relates moisture content of a soil to the moderation of fast neutrons. Fast neutrons are moderated by hydrogen (a constituent of water) in the soil and the resulting slow neutrons are detected and counted by a scalar. The water content is directly related to the slow neutron count, assuming that free water is the only material in the soil containing significant amounts of hydrogen.

Gradation of Granular Base Materials

Although the gradation of granular base course material is important and is properly included, at some point, in most highway specifications, the basic method employed to obtain gradation of these materials has changed very little in recent years. A search of the literature exposed a few papers on this subject and most of these are concerned primarily with aggregate quality or gradation at the source and in the stockpile. An example of this type of research is reported in *NCHRP Report 46* (*55*). A recent study by Gunn (*56*) was concerned with the degradation and densification of aggregate base material under traffic but had no reference to rapid test methods for determining gradation.

Other research efforts in the gradation area found in the literature search are applicable to the classification of soils and other fine-grained material and are typified by the work of Chu and Davidson (*57*) and Handy and Davidson (*58*). The laboratory equipment described by Coulter and Kinsman (*59*) uses the resistance change principle to electronically count and measure the size of particles passing through a small orifice and is applicable to particles under 1 mm in diameter.

A relatively rapid test method frequently mentioned in the literature and which has some relationship to gradation is the "sand equivalent test." This test was introduced by Hveem (*60*) of the California Division of Highways and is designed to enable the field engineer to detect the presence of clay and undesirable fines in soils, gravel base material, etc. The test is based on volumetric measurement; about 40 min are required to complete each determination. Although this test time seems long in terms of "end-result" testing, the test is useful in checking the suitability of natural base material prior to removal from a given select material borrow or gravel-pit source.

Informal efforts to increase the speed of gradation testing in the field occasionally come from personnel connected with highway departments who have designed and built auxiliary devices such as warm air dryers and mechanical sieve shakers. However, portable gasoline-powered and hand-crank-operated shakers as well as field heaters are available from commercial test equipment firms and it is doubtful if custom-built equipment will do much more than commercial equipment toward reducing the time required to run a mechanical analysis in the field.

Compaction Criteria for Granular Materials

Specifications for base course material normally require that compacted density be some percentage of a standard density. Maximum density for soils is controlled by compactive effort, moisture content, and gradation. As the percentage of larger grain size material increases in a soil sample, the influence of gradation becomes more pronounced. Moisture content, on the other hand, becomes less critical as the amount of fines (minus No. 4) decreases. Some water, however, is necessary to obtain specified densities; but the amount of water is usually not critical and is varied by trial and error until sufficient density is obtained. Ideally, the standard or maximum density test should be performed on a sample that completely represents the material to be compacted in the field (*61*). Field tests for making this determination are almost nonexistent and most laboratory procedures depend on a theoretical or empirical correction for the large-grained material.

Methods that provide compaction criteria for granular materials may be classified as impact methods, vibratory methods, use of standard curves, or field compaction of test sections. None of these methods is considered rapid in terms of tests that require only a few minutes to perform. However, base course material is normally more uniform and more easily controlled than soils that might be used for embankment and subgrade construction. For this reason only a limited number of standard density determinations are required for base material, whereas soils sometimes require one for every density test.

Impact Methods

Both the standard and modified AASHO procedures (T 99 and T 180) may be used for soil-aggregate mixtures with ¾-in. maximum size aggregates. Studies by Mainfort and Lawton (*62*) have shown that these procedures may be used successfully for soil-aggregate mixtures having 1½-in. maximum size. These test results, however, become erratic as the amount of material larger than a No. 4 sieve aperture exceeds 80 percent. Also, it was found that degradation of the larger particles begins when the coarse fraction (plus No 4) is more than 30 percent of the total sample

The method used by the U S. Bureau of Reclamation, designated E-38 (*63*), can accommodate a 1½-cu-ft sample with a 3-in maximum particle size. The equipment required for this test is very large and must necessarily be operated only in the laboratory

California also uses an impact procedure (*51*) that produces a compactive effort similar to the AASHO T 180 method However, this test is designed primarily for soils as it is performed only on material smaller than ¾ in.

Vibratory Methods

Johnson and Sallberg (*64*) describe vibratory compaction test equipment and procedures used for maximum unit weight determination of cohesionless sands and gravels They tabulate 15 different methods which may be broadly categorized as either sustained vibration or momentary vibration created by hammering on the sides of the mold. Ten of these methods have been studied by the American Society for Testing and Materials (ASTM) and four are listed as ASTM suggested methods.

Pettibone and Hardin (*65*) have recently reported on an investigation of the combination of variables that will give the highest laboratory maximum density. Various electromagnetic table-type vibrators were used

Studies using samples with a ¾-in maximum aggregate size have been carried out by Chamblin (*66*), who used a vibrating table. Unit weights produced by vibration were compared to those produced by standard methods The laboratory compaction generally produced densities as high as those obtained in the field, whereas AASHO and ASTM standard densities were found to be less than the densities easily obtained with field compaction equipment

Humphres (*67*) has described laboratory equipment currently used by the Washington State Highway Commission which applies a static load as surcharge in addition to vibratory effort supplied by hammering on the sides of the mold. Two density determinations are made in this procedure—one on the minus No. 4 fraction of the sample in a standard CBR mold, and the other on the plus No. 4 material using a larger mold. The two densities obtained in this manner are used for end points on a unit weight-gradation curve where the intermediate points are supplied by charts or computer programs. Humphres (*68*) has indicated that similar equipment is available for field use

Standard Curves

Most compaction tests on granular material require a correction for oversize material, and formulas and charts have been developed for this purpose.

One of the early correction equations to be formulated has been evaluated by Zeigler (*69*). This equation is based on the assumption that void spaces that normally would occur in the coarse fraction are completely filled with minus No 4 material Zeigler found that the actual density of the soil-aggregate mixture was somewhat less than the calculated density, and for mixtures having greater than 30 percent plus No. 4 material this deviation increased considerably. Mainfort and Lawton (*62*) investigated the equation just mentioned and found it to be in error. They also studied the correction formula specified by the Civil Aeronautics Administration (*70*) and found it to be reasonably accurate for soil-aggregate mixtures having a quantity of plus No 4 material equal to or less than optimum. However, when the coarse fraction exceeds 40 percent of the total sample, the calculated density exceeds that which can be obtained by compaction tests

Turner (*71*) introduced a correction chart into the Missouri specifications that takes into consideration the two cases where the fines are either excessive or insufficient to fill the voids of the coarse aggregate. Humphres (*67*) presents an elaborate correction procedure that covers eight different combinations of fine material either replacing coarse material, filling voids, or vice versa Each of these combinations is illustrated with a block diagram by James and Larew (*72*), who conducted laboratory compaction tests verifying Humphres' curve

Test Sections

The wide variations of correction formulas, laboratory test procedures, and standard curves have led investigators to compare these procedures with actual field compaction of granular materials. One such study conducted by Nichols and James (*73*) has resulted in the recommendation that compaction criteria be based on the maximum density obtainable in the field. Test sections of base material were compacted with as many as 50 passes of a heavy roller. The densities obtained were correlated with the amount of coarse aggregate and a regression analysis was used to construct a density-gradation curve. Values obtained from this density-gradation curve exceeded values obtained from both the AASHO method T 99-C and Humphres' curve. However, densities obtained by a vibrating table method generally exceeded field densities.

Moisture Content of Soils and Granular Materials

Determination of moisture content is necessary in the compaction control of soils and granular materials. Various methods have been investigated for rapidly measuring moisture content. Most of these methods are based on some physical, chemical, or electrical property of the soil-water mixture as well as the nuclear properties of hydrogen that were discussed previously.

Physical Methods

There is a wide variety of physical methods for moisture determination. Several of these procedures simply remove the water by a drying process and compare the net weight of the soil-water mixture to its dry weight The standard laboratory procedure is to place the sample into a drying oven maintained at approximately 105°C Alcohol burning (*74, 75*) is another method for removing soil water that can readily be performed in the field. Houlnick (*76*) describes a method that requires approximately 30 min and uses infrared radiation from a lamp to dry a 100-gm sample. Thermistors have been used by Bloodworth and Page (*77*) as a combination heating element and temperature indicator to obtain soil moisture content.

Perrier and Evans (*78*) have reported the evaluation of various tensiometers that measure capillary tension in the soil pores. When properly calibrated, these instruments can be used for determining moisture content. However, tensiometers will not respond near saturation moisture content, and low water content measurements require a much longer response time for accurate readings.

Other measurements that may be used to determine moisture content are the buoyant weight or displaced volume of the solid soil particles. Kirkham (*79*) describes a buoyancy moisture meter that consists of a balance arranged so that a long-handled sample bucket hung from a beam is immersed in water. The instrument and method are well suited for granular materials up to 1½ in. in size; about 4 min are required to make a determination. McIntosh (*80*) reports on a "siphon can" similar to one used by the U S. Bureau of Reclamation. The sample is immersed in a container, and a special transparent scale permits a direct reading of moisture content as indicated by the displaced water Displaced volume may also be measured by the pycnometer method (*74*), which is similar to the ASTM procedure for bulk specific gravity determination

Moisture content of soil, particularly fine-grained soil, is related to its strength Methods such as the "drop test" (*81*) and the hydraulic Proctor needle (*82*) have been developed on this principle. In both of these procedures the soil sample is compacted in a mold The penetration test using the Proctor needle is conducted with the soil in the mold, whereas for the drop test the sample is removed from the mold and dropped from a fixed elevation. The depth of needle penetration and the reduced height of the dropped specimen are correlated with moisture content. These methods are applicable only to cohesive soils at or near optimum moisture contents.

Chemical Methods

The chemical methods used to determine moisture content consist of mixing moist soil with either a powdered substance or liquid which will then extract or react with soil water. The most popular of these methods is the calcium carbide gas pressure method reported by Blystone, Pelzner, and Steffens (*83*). The gas produced by the chemical reaction creates a pressure that activates a gauge specially calibrated to read moisture content directly. Steffens and Ring (*84*) describe another calcium carbide method in which the generated gas is allowed to escape. The loss of weight of the soil sample after the reaction has been completed is then used to determine the moisture content from the chemical equation for the process. This procedure is well suited to large samples of granular material; however, its accuracy is somewhat questionable (*85*).

Miscible liquids are also used to extract the pore water from the soil-water mixture Bonar (*86*) describes the alcohol solution method, where the specific gravity of the water-alcohol mixture, after it is removed from the sample by filtering, is compared to the specific gravity of the pure alcohol The moisture content may then be calculated or read directly from special hydrometers (*74*). Other liquids such as glycerol, pyridine, and dioxane are used to extract water (*85*) The amount of water extracted has been correlated with the change in refraction index of these fluids as they are mixed with water. Only one drop of this liquid is necessary for the refraction test, and simplified refractometers are available for field use. The dielectric constant of these liquids may also be determined and correlated with the amount of water present in the solution (*87*). Hancock and Hudgins (*88*) have used similar extraction procedures and used the conductivity of the liquid extract as an indicator of moisture content. Their method has been further developed (*89*) and has been applied to determinations of moisture in cottonseed meats and meal.

Electrical Methods

These methods measure electrical properties of the soil-water mixture itself. Conductance, or resistance, and capacitance of the soil-water system have been measured with various devices Conductivity gauges have been successfully used to measure the moisture content of concrete sand (*90*). Polarization of electrodes of the device is a major handicap; however, this effect is usually minimized by the use of alternating current, although direct current may be used if the equipment is modified (*91*). Calculations for the foregoing methods can be simplified by use of a slide rule developed by Rowland, Fagan, and Crabb (*92*).

A capacitance meter for field use that measures the electrical capacity of the soil in less than a minute is described by de Plater (*93*). Special probes have been designed (*94*) to facilitate their insertion into the soil

In-Place Density of Soils

Most of the discussion under the heading of "Density of Granular Base Materials" presented earlier and by Redus (*95*) applies equally to embankment and subgrade soils. The oil replacement and drive-tube sampling methods have limitations in determining density of soil. However, both of these methods are considered rapid.

The Georgia Highway Department has a specification procedure (*96*) for the tube sampling method, and Florida frequently uses the oil replacement method (*97*). Both of these procedures work best in fine-grained, cohesive soils. Any rock fragments larger than ¼ in. cause difficulty in the drive-tube method. Some degree of skill is required to drive the sampling tubes into the soil so as to cause the least amount of disturbance of the density sample; the ends of the sample must be carefully trimmed before being weighed. The Georgia method provides for the use of a tube having a volume of 62.5 cc. Thus, the sample weight in grams for this size of tube is equal to the unit wet density of the soil in lb/cu ft.

The accuracy of the oil replacement method is seriously affected by any seepage that may occur while the oil is being poured into the hole. For most saturated clays the amount of seepage is negligible. For soils of greater permeability the "double oil" method may be used whereby the hole is first filled with oil that is allowed to stand until the seepage rate decreases. After equilibrium is reached all the oil is removed to prepare the hole for a second filling. The amount of oil required to fill the hole the second time is recorded as the volume. Although accuracy is considerably improved by this procedure the time required to perform the test is more than doubled.

Compaction Criteria of Soils

Compaction control criteria based on the moisture-density relationships of soils has had widespread use since the Proctor method was first introduced in 1933 (*98*). Hveem (*99*) outlines the historical development of the various compaction test procedures in common use and compares the Proctor-type methods with the long-established California impact method. These test methods, including the AASHO designations T 99 and T 180, have general similarities in which compaction of the test sample is accomplished by the impact of a 2-in.-diameter rammer. Except for the California method, all of these methods are long and tedious. At least four points on the moisture-density curve should be run, and often more than 2 hr is required to complete the test. If the AASHO T 99 test procedure is performed on the actual soil being compacted in the field, as much as 2 to 3 hr could elapse before an acceptance decision is reached.

The California impact method is, however, more rapid than the other "standard" methods and is described in more detail later in this report. Variations of the other methods also have been developed which reduce the time required to determine the standard maximum density and optimum moisture content of the soil being compacted in the field. One of these procedures that reduces the required number of operations is the Hilf method (*100*). This method is used by the U.S. Bureau of Reclamation and is known as "Rapid Compaction Control," Designation E-25 In this method, the soil is compacted, in the mold, at the field moisture content. A second point is run at higher moisture content and a third point is run at higher or lower moisture content, whichever is necessary to bracket optimum moisture. Using these points, a parabolic curve is drawn and the required change in fill moisture to reach maximum density is determined, even though the actual moisture content is not known.

Another variation of the AASHO method is the "one-point" Proctor (*101*) which is currently used by New York, Ohio, and Wyoming. This method, described by Steffens and Ring (*84*), is based on the theory that the moisture-density curves for most soils will be similar in shape for the same compactive effort. A family of curves covering soils from high maximum density and low optimum moisture, to soils with low maximum density and high optimum moisture is drawn from laboratory compaction tests of a great variety of soils in the area. The Proctor needle penetration resistance of these typical soils is also recorded for different moisture contents on the family of curves. In the field, a sample of soil from the embankment or subgrade is compacted in the Proctor mold at or near optimum moisture. The moisture content of the sample is then determined by means of the Proctor needle. This information and also the density of the compacted sample are used to identify the soil. The maximum density indicated by the typical curve for the particular soil is then used to compute relative density of the embankment or subgrade. As long as the soil being tested in the field can be identified by one Proctor test, other points on the moisture-density curve of the soil need not be run and the total time required for the determination of maximum density is greatly reduced. However, in cases where it is not possible to identify the soil by the "one-point" method, additional tests are needed to complete the compaction curve.

Other test procedures have been developed that also reduce the time required to determine the moisture-density relationships of soils. One of these methods, used by the Oregon State Highway Department (*102*), employs the Harvard miniature compactor and is described in more detail later. Some of the advantages of this method are that less physical effort is required to compact the sample and the equipment is supplied with an extruder that simplifies sample removal. Also, fresh soil may be used for each point of the determination because the quantity of soil required to fill the 1⁵⁄₁₆-in. diameter mold is very small.

The interrelationships between compaction test data and other laboratory test data have been explored in the hope that the Atterberg limits and mechanical analysis might be used as compaction criteria. A recent study by Ring, Sallberg, and Collins (*103*) shows that some correlation between these parameters does exist and that optimum moisture content and maximum dry density can be predicted from the plastic limit and gradation characteristics. However, this prediction is not sufficiently accurate to take the place of compaction tests. Further, if field use of this method of compaction control were attempted, it would be necessary to identify soils in the field as representative of a laboratory sample with particular plasticity and gradation characteristics. The same problem of identification occurs when laboratory compaction tests are run on samples taken from the construction site prior to compaction in the field.

Another approach to compaction control has been proposed (*104*) in which the degree of compaction is specified in terms of maximum permitted percentage of air voids.

In a study of elastic subgrades by Rostron (*105*) it was noted that saturated soil samples compacted in a consolidation apparatus using 100 load applications at 43.4 psi achieved a sample density equal to approximately 95 percent compaction (based on the AASHO T 99 procedure) for most soil samples tested. The soil moisture in the sample after compaction by the foregoing procedure was related to, but higher than, the optimum moisture content.

Vibratory compaction test methods for sandy, cohesionless soils have been studied by Pettibone and Hardin (*65*). Previous investigations have shown that, for most cohesionless soils, higher densities are attained by vibratory methods than by standard impact compaction methods.

The discussion of compaction criteria has, thus far, been confined to literature related to maximum dry density obtained by the use of various common compaction test procedures Because the primary objective of compaction is to obtain maximum strength and stability of the subgrade, some investigators have suggested tests that measure the strength of the soil directly rather than by using density as an intermediate criterion. An example of this approach, discussed by Turnbull and Foster (*106*), is proof-rolling of the subgrades with a heavy roller. Proof-rolling will, under limited conditions of moisture, further compact the soil and also will reveal weak spots that may exist in the subgrade. Proponents of proof-rolling have stated that the primary objective of this procedure is to discover weaknesses that are associated with the type of soil found in the finished subgrade rather than deficiencies in the degree of compaction.

Penetrometers, which are inherently rapid testing devices, also have been suggested for measuring the strength of the subgrade. Singh and Ranjan (*107*) have shown that the bearing capacity of fine-grained soils, as determined by the North Dakota cone test, can be correlated with the CBR of the same soils. They suggest that if the moisture content of the soil is known, the density can be predicted from the penetration resistance of the soil. Housel (*108*) has developed an impact penetrometer in the form of a tube sampler that also can be used to obtain an undisturbed sample of the soil if desired.

Murayama, Ueshita, and Saito (*109*) have developed the "ball drop test" to determine rapidly the CBR-value of the subgrade. This is accomplished by measuring the diameter of the depression produced on the surface caused by dropping a spherical ball from a specified height. Two clean sheets of paper enclosing a sheet of carbon paper are put on the subgrade to obtain a print of the impression.

Asai (*110*) has applied energy methods to derive a relationship between the initial deflection of a 30-cm-diameter plate and the modulus of subgrade reaction.

Portland Cement Concrete Paving

This portion of the literature review is devoted primarily to test methods that are applicable to plastic concrete; however, some attention also is given to strength tests of hardened concrete. The review is presented in five parts, as follows: (1) cement content, (2) water content and water/cement ratio, (3) air content, (4) workability, and (5) strength.

Cement Content

The cement content of concrete mixes used in highway paving has a direct effect on strength of the hardened concrete. It would appear, therefore, that a direct attempt should be made to determine cement content of plastic concrete.

Dunagen (*111*), Murdock (*112*), and Kirkham (*113*) each reported on test methods that involved screening the concrete on a No. 100 sieve and assumed that all material that passed this sieve was cement. The assumption that all material passing the No. 100 sieve is cement leads to large discrepancies in the results.

Chadda (*114*) reported on both an electric conductivity method and an absorption method to determine cement content. The first method has the fault that it does not consider moisture contributed by fine and coarse aggregates. The second method is subject to operator interpretation and is based on the differential absorption characteristics of cement and fine aggregate.

An electrical conductivity method for determining cement content of fresh concrete, using a 1-lb sample and a conductivity cell with probe, has been experimented with in the state of Washington (Sec. 12.208, *Construction Manual for Engineers*).

Covault and Poovey (*115*) initiated research to study the distribution of cement in concrete in a mixer, operating under given conditions of mixer time, type of mixer, etc. Their method of detection of cement involved the use of neutron activation. This equipment is expensive and test results are based only on determination of calcium content of the mix Because many aggregates have calcium particles, this method of detection, although fairly accurate and rapid, cannot be applied to all concretes

Hime and Willis (*116*) developed a heavy-media separation method for separating cement from fine aggregate and cement in a fluid with a specific gravity between that of the aggregate and cement. The fine aggregate floats, whereas the heavier cement does not, thus providing a means of determining the percentage of fine aggregate in the mixture.

The "heavy media" used by Hime and Willis was a mixture of carbon tetrachloride (s.g. 1.59) and acetylene tetrabromide (s.g 2 96), adjusted so that the specific gravity of the fluid was 2 80. Fineness modulus of the sand and type of cement had only a negligible effect on the results This method of measurement was reported to be accurate to about ¼ sack of cement per cubic yard. The test time was about ¾ to 1½ hr. The methods used by Hime and Willis were incorporated as an ASTM tentative test method (*117*).

Walker et al. (*118*) pointed out some of the problems encountered in using the method of Hime and Willis, such as the difficulty in securing a small representative sample of fresh concrete and the necessity for meticulous care on the part of trained technicians under laboratory conditions.

The separation of cement particles from other constituents of plastic concrete is a difficult problem. Butler (*119*) in conjunction with NCHRP Project 6-6 (To Evaluate Existing Methods and/or Develop Improved Methods for a Measurement of Certain Properties of Concrete)* reported on a test method that involved the physical separation of the material that passed a No. 100 sieve, with a second test to correct for the fine aggregate in this material. The test sample was ⅓ cu ft in size The test procedure

* Report summarized under "Summaries of Unpublished Reports," *Summary of Progress to June 30, 1967*

consisted of washing the fines through a No. 100 sieve and determining the specific gravity of the resulting slurry. A sample of the slurry was then dried and the ratio of cement to fine aggregate in the slurry was determined by centrifuging in a heavy-medium liquid of acetylene tetrabromide diluted with kerosene. It was reported that this test method was subject to errors that could be as large as one-quarter sack of cement per cubic yard. The required test time for two technicians was 30 to 40 min.

Water Content and/or Water-Cement Ratio

Very little was found in the literature on rapid means of determining water content or the water-cement ratio of plastic portland cement concrete.

Glegg (*120*) developed an apparatus for determining the water content of a concrete mix. A London firm (*121*) marketed an electrical device called the ratiometer that had a small vibratory unit in the head of a probe. The vibratory unit is submerged in plastic concrete to bring a slurry to the surface and to measure its electrical resistance. By comparing field resistance measurements with laboratory test results on similar mixes one could evaluate water-cement ratios of the field mix. No data were found to substantiate these claims.

A portable nuclear instrument similar in principle to the nuclear moisture gauge has been developed in Canada to measure the hydrogen content of hardened concrete (*122*). The slow neutron count registered by the gauge does not differentiate between free water and water in hydration compounds; therefore, the accuracy of this method may be adversely affected.

Butler (*119*) also reported on preliminary explorations at Ohio State University to determine the water content of fresh concrete by neutron scattering. He used both a Nuclear-Chicago Model P-19 depth moisture gauge and a Nuclear-Chicago Model P-21 surface moisture gauge. Butler reported that for a 5.5-gal-per-sack mix, the surface gauge accuracy was ±4 percent, or an error of 0.22 gal of water per sack. With normal concrete this corresponds to about ±200 psi compressive strength at 28 days.

Air Content

One of the most important test items needed in the concrete paving field is a rapid and accurate means of determining the amount of entrained air in the concrete. The type of air for which a measurement is desired is that which is distributed in minute droplets throughout the concrete.

One recognized method for measuring the volume of air within a plastic concrete mix is the pressure method of ASTM C 231-62 (*123*). The development of the pressure method is credited to Klein and Walker (*124*). Two basic types of pressure meters are now in use; the Menzel type (*125*) uses water and applied air pressure, whereas the Washington type (*126*) uses air pressure but no water.

The Washington air meter differs from the pressure apparatus of the Menzel type in that no water is used and it operates on a variable pressure principle. In the Menzel type (ASTM C 231-62) the working pressure for all testing is about 7.5 psi and is predetermined in the calibration of the apparatus. In the Washington meter the air in the upper chamber is brought to about 14 psi and then air from this chamber is transferred by a valve to the concrete in the lower chamber. This equalizes the pressure in both chambers, and the change in pressure is a reflection of the air voids in the concrete. Klieger has reported on methods of determining aggregate air void correction factors for the Washington meter. Such correction values have been shown by several investigators to be significant (up to 1.5 percent for natural aggregates). The Washington air meter uses a 0.25-cu-ft sample of concrete, does not use any water, and corrections are not necessary for ground elevations. It does not require any scales and is relatively light. Single tests for air in concrete can be made in 10 min, provided aggregate correction factors are known.

Another widely recognized method for determining air content of fresh concrete is the "volumetric method" of ASTM C 173-58 (*127*). The same minimum-size measuring bowl as that for the pressure method is specified.

In this method of test the concrete is covered with water and is agitated by rolling the instrument until it appears that the air has been released from the concrete. The instrument is easily calibrated so that the change in water level can represent the volume of air released from the concrete. The entire test can be completed in 10 min.

The Chace or AE-55 air meter, a small volumetric measuring device, has shown much promise as a rapid method for measuring air content of small samples of mortar taken from plastic concretes. Grieb (*128*) and others have reported good correlation between results obtained with the AE-55 meter and those obtained from standard pressure methods which test about 0 20 cu ft of concrete. Mather (*129*) reported that on many tests conducted at the Waterways Experiment Station he found that results from the AE-55 meter differed from those of the pressure method by values of only ±0.6 percent for two-thirds of the tests when air contents were below 3.0 percent. This difference dropped to ±0 5 percent for two-thirds of the tests when air contents were over 5 percent. These values held only when correction factors were used from Grieb's curve relating values from the two methods

The AE-55 air indicator was tested extensively by Newlon (*130*) in field practice and found to be very suitable. The air meter uses the principle of volumetric displacement of entrained air from a 3.7-ml sample of mortar; hence, it is not as accurate as some other available methods. This instrument does have the advantage of being small, inexpensive, and simple to operate. Air contents can be found in 3 min or less. To use the AE-55 air indicator one must use material that passes the No. 10 sieve.

Newlon found the meter to read high at low air contents and low at high air contents; his comparison was with results from pressure meters of the Protex and Washington type. In general, the meter gave air contents within one-half a percentage point of those given by the pressure meters.

The removal of air from concrete presents a problem in any volumetric test method. Pigman (*131*) introduced the idea of using a vacuum in which the air is removed at a reduced absolute pressure of about 17 mm of mercury. This method, although apparently satisfactory for laboratory work, is not suitable for field testing.

The air content of hardened concrete has been measured by two methods; namely, a high-pressure method and a linear-traverse method.

Erlin (*132*) has reported on portable equipment designed to determine air content of hardened concrete by a high-pressure method. The equipment he used was a modification of that used by Lindsay (*133*). The theory of operation of the equipment is predicated upon the assumption that water under the test pressure of 5,000 psi will penetrate the concrete and compress the air in the voids to a very small volume. The equipment was designed for testing a standard 6-in. by 12-in. cylinder. When a suitable correction factor for the aggregate is used, results compare favorably with those obtained on the fresh concrete by pressure-meter methods, and somewhat less favorably with those found by the linear-traverse method.

The linear-traverse method is considered to be the most accurate method of determining air content, and provides data to compute percentage of air voids as well as size and distribution of the air voids. It is recognized that the size and distribution of voids is of primary importance in governing the durability of concrete. Equipment for this method was introduced for measurements on concrete by Verbeck (*134*). It was further developed by Rexford (*135*), Brown and Pierson (*136*), and Warren (*137*), and has been used by many researchers in recent years in studies where scaling of pavements has been a problem. The linear-traverse test is a lengthy test and cannot be classified as rapid

Workability

One of the requirements for plastic concrete is that it be workable, but not so workable that segregation occurs. This quality of workability has often been called "consistency."

The slump test (ASTM C 143) has been accepted for years as a measure of this consistency, and most job specifications refer to it when mentioning field control of mixes. One determination of this test, when made properly, will take approximately 10 minutes.

Kelly and Haavik (*138*) introduced the Kelly ball, which is now a standard test described in ASTM C 360-63. Howard and Leavitt (*139*) noted that one reading for this test could be obtained in approximately 10 sec, and a factor of 2 could be used with very good accuracy to translate Kelly ball readings to slump-test values. However, Kelly later wrote (*140*) that this factor would vary somewhat with various mixes.

The Kelly ball is a rapid test method and permits the testing of concrete in delivery buckets without disturbance. About the only limitations to the test appear to be that the equipment must be placed on at least 6 in. of concrete and the maximum aggregate size should be 2½ in.

Marr and Grieb (*141*) reported on a modification of the feet of the reference frame of the Kelly ball equipment. This modification is a part of the equipment described in ASTM C 360-63.

The Vebe consistometer test (*142*) was developed in Sweden and has not had wide use in America. In this test, concrete in a slump cone is vibrated to optimum compaction with standard vibrating equipment. The time in seconds to reach this condition is known as Vebe degrees.

A cone penetrometer was recently devised and used by Cordon (*143*) in his study of workability of concrete mortars. Penetration of the cone into mortar was taken as a measure of slump or workability.

Hughes (*144*) describes an apparatus developed to determine the resistance to segregation of fresh concrete, which may be applicable to the control of workability at the job site.

Some engineers and agencies have experimented with devices to indicate the workability of mixes while they are still in the mixer. One such device, a recording wattmeter, was devised to measure the changes in power required to turn the mixer as the batch varies from dry to wet. Another device, a "Plastograph" invented by Glenway Maxon, was tested at Allatoona dam with some degree of success (*145*) The current from probes connected to reaction blades within the mixer varied with the workability of the concrete.

The subject of "consistency" or workability of concrete has been discussed at length by Popovics (*146*). Although his paper did not introduce any additional rapid test methods, he did show by theory and test that the relationship between slump and mixing water is not linear, as is generally presumed.

Strength

For many years the rule of strength of concrete being directly proportional to the water-cement ratio (*147*) has been used and expounded on by technologists in the concrete field. Gilkey (*148*) called attention to other factors that affect strength.

The operation of the soniscope (*150-155*) and the "elastiscope" (*156*) is based on the ultrasonic pulse principle, which has been used to evaluate the strength of hardened concrete.

Several factors, such as the aggregate-cement ratio, influence the pulse velocity. Therefore, this method cannot be used to compare differences of strength between various concrete mixes accurately. Thus, it is primarily useful as a tool to measure gain or loss of strength in a particular specimen. It has been used as a crack detector, because any crack in the concrete interrupts the pulse. Investigators have reported that the soniscope is a useful technique when used in outlining areas of poor concrete in structures.

Kaplan (*157*) also found that the pulse velocity was a function of several items, including aggregate-cement ratio, water-cement ratio, and age. This complex relationship makes it almost impossible to predict 28-day strengths accurately by measuring impulse velocities at 3 days or earlier unless much prior experimentation has been done with identical mixes.

A summary of ultrasonic and resonant-frequency devices was given by Whitehurst (*158*). A Highway Research Board symposium (*159*) indicated that some investigators who were acquainted with these testing devices questioned their usefulness for testing highway pavement slabs. Kozan (*160*) reported on the successful use of this type of equipment.

The Swiss or Schmidt rebound hammer (*161-167*) has been used for the evaluation of relative strength of hardened concrete. This equipment consists of a spring-loaded plunger which, when released, strikes against the surface of the material The spherical end of the plunger indents the material, and the distance the plunger rebounds is read from a scale as a "rebound number." This quick, simple test yields rebound numbers that must be correlated with concrete strengths by means of extensive laboratory tests on concretes of similar coarse aggregates.

King (*168*) has reported the development of an accelerated test that involves heating the freshly poured concrete specimen for 6 hr with subsequent testing King found some relationship between results of the accelerated test and standard 20-day strengths. But, to make the test workable, complete prior calibration tests must be conducted on the same mixes as those used in the field

Other investigators (*169, 170*) have experimented with accelerated curing methods on test cylinders in an effort to find a correlation between standard 28-day strengths and strengths at a much earlier date for cylinders cured in an accelerated manner. Malhotra et al. (*171*), recently reported on such tests. Cylinders were cured in a moist room for 24 hr and then were placed in boiling water, complete with steel molds and covers, for 3½ hr. After cooling for 45 min, the cylinders were capped and tested. The total elapsed time between molding and testing was 28½ hr. The relationship between accelerated-cured strength, X, and 28-day standard cured strength, Y, was not linear, but was represented by a curve of the type

$$Y = X/(AX + B) \tag{1}$$

in which A and B are constants. Malhotra et al. obtained an accuracy of ± 12 percent with this equation for predicting 28-day compressive strength from accelerated test results.

Another testing program that used accelerated curing was reported by a Swiss laboratory (*172*). Good correlation was obtained between 28-day compression strengths of cement mortar cube specimens and cube specimens cured normally for 24 hr and then heated in an autoclave under 12 atmospheres of pressure and steam for 7 hr. However, test results for flexural strength showed that accelerated specimens had less strength than standard-cured 28-day specimens.

Grieb and Werner (*173*) have found splitting tensile strength test results on concrete cylinders to be directly proportional to, but more reliable than, flexural strength test results They also found that the relation between the splitting tensile and compressive strengths was curvilinear. They therefore suggested that the relatively simple splitting tensile strength test be substituted for the conventional flexural and compressive strength tests for evaluating concrete for highway pavements.

STUDY OF CURRENT PRACTICE

One facet of the initial phase of this project was to determine current practice of test procedures in highway construction. This was obtained by personal interviews, questionnaires, and by inspecting standard specifications and testing manuals from various states. Thirty-three states completed the questionnaires, 36 supplied standard specifications, 22 supplied manuals, and 15 were visited personally by the researchers to obtain a general picture of current practice.

Table 2 indicates the degree with which various AASHO and ASTM standard methods of test (and slight modifications) are mentioned in specifications and manuals. Some test methods that are not field tests are included in Table 2 because they are often used in a central laboratory to check samples sent to it from the field.

Data obtained from questionnaires also are summarized in Table 2. An analysis of the data indicates that the majority of state highway departments still make general use of standard or slightly modified AASHO and ASTM test procedures for field control of construction. Actual use is approximately 75 percent for AASHO and ASTM procedures; about 25 percent of the testing consists of the use of special test procedures Answers to the questionnaire indicated that about 80 percent of the special test procedures are considered to be rapid, whereas only 17 percent of the AASHO and ASTM procedures are classed as rapid test methods.

The following discussion of current use of test methods for field control of construction is divided into three categories: (1) tests pertaining mainly to asphaltic mixtures, (2) tests pertaining mainly to subgrade and base course construction, and (3) tests pertaining mainly to portland cement concrete

Asphaltic Mixtures

Test methods pertaining to control of asphaltic mixtures in highway construction include the evaluation of stability, asphalt content, and density.

The determination of stability is seldom performed in the field. When a check is made at the job site the Marshall method normally is used.

Field determination of the asphalt content of asphaltic mixtures generally is accomplished by the centrifuge method. Nuclear methods are available for in-place asphalt content determination and are in limited use.

Bulk density determinations normally are made by immersing coated or uncoated specimens in water. Major exceptions include the use of the volumeter by Ohio and limited use of in-place nuclear methods. The major problem in density determinations is the removal of a representative sample from the pavement This is being done in a number of ways such as by coring or sawing, or by the use of a split ring, a paper cup, or a hammer and chisel

Subgrade and Base Construction

There are many test methods in current use for determining in-place density, compaction test maximum density, moisture content, and gradation of embankments, subgrades, and bases.

TABLE 2

SUMMARY OF CURRENT USE OF TEST METHODS FOR CONSTRUCTION CONTROL AS INDICATED BY QUESTIONNAIRES, STANDARD SPECIFICATIONS, AND TEST MANUALS

PROPERTY	INDICATED USE OF TEST METHODS, FROM QUESTIONNAIRES (%)		FREQUENCY OF MENTION OF TEST METHODS IN SPECS AND TEST MANUALS		
	AASHO OR ASTM	OTHER	TEST METHOD AASHO	TEST METHOD ASTM	NO. OF STATES (%)
Asphaltic mixtures.					
Strength and stability	—	—			
Marshall method	—	—	—	D 1559	10–30
Hveem method	—	—	—	D 1560	<10
Hubbard-Field method	—	—	T 169	D 1138	<10
Unconfined compression	—	—	T 167	D 1074	<10
Asphalt content	95	5			
Centrifuge	—	—	T 164	D 1097	10–30
Reflux	—	—	T 184	—	<10
Reflux	—	—	T 170	D 762	<10
Specific gravity	70	30			
Water-immersion			T 166	D 1188	10–30
Aggregates and soils:					
Grain size analysis	85	15			
Finer than No. 200 (agg.)	—	—	T 11	C 117	30–60
Finer than No 200 (soil)	—	—	—	D 1140	<10
Sieve analysis (agg.)	—	—	T 27	C 136	30–60
Sieve analysis (soil)	—	—	T 88	D 422	10–30
Sand equivalent test	—	—	T 176	—	<10
In-place density	70	30			
Sand cone, oil	—	—	T 147	D 1556	30–60
Filler-ring	—	—	T 181	—	<10
Moisture-density	80	20			
Standard	—	—	T 99	D 698	30–60
Modified	—	—	T 180	D 1557	10–30
Penetration	—	—	—	—	—
Soil penetrometer	—	—	—	D 1558	<10
Moisture content	65[a]	35			
Portland cement concrete					
Compressive strength	90	10			
Cylinders and cores	—	—	T 22	C 39	30–60
Beam portions	—	—	T 140	C 116	10
Flexural strength	100	0			
Third-point loading	—	—	T 97	C 78	30–60
Center-point loading	—	—	T 177	C 293	10–30
Air content	80	20			
Pressure method	—	—	T 152	C 231	30–60
Gravimetric method	—	—	T 121	C 138	10–30
Volumetric method	—	—	—	C 173	10–30
Consistency	100	0			
Slump	—	—	T 119	C 143	60
Kelly ball	—	—	T 183	C 360	10–30
Cement content	35	65			
Hardened concrete	—	—	T 173	C 85	0
Soil-cement mixtures:					
Cement content	—	—	T 144	D 806	10
Moisture-density	—	—	T 134	D 558	10–30

[a] Percentage refers to conventional heating-type test methods rather than standard AASHO or ASTM test methods

Ordinarily, dry density is determined for compaction control. However, California and the U.S. Bureau of Reclamation have alternate methods that use wet weights and eliminate the drying operation.

The sand-cone method is probably the most commonly used present-day method for determining field density. California uses an oversize sand apparatus to permit in-place density measurements of rocky materials. Another variation, used to some extent by South Carolina and Colorado (*174*), involves the use of a cylindrical plug of known volume which is inserted in the test hole. Thus, less sand is required to fill the remaining volume. This minimizes errors due to vibration and sand calibration and permits larger holes to be filled with a given quantity of sand.

Water-balloon equipment also is widely used for in-place density tests. The Washington densometer, the Rainhart balloon apparatus, and the Soiltest volumeasure are examples of this type of equipment. All of these devices tend to increase the speed of density testing because the volume of the hole is read directly from the apparatus and the surface to be tested does not have to be perfectly level. The Washington densometer has the additional advantage of large capacity (up to 0.5 cu ft) so that densities can be obtained for rocky materials containing unusually large particles.

Florida uses the oil method about 20 percent of the time, whereas Georgia sometimes uses a drive cylinder (Georgia Highway Department method GHD-30) on fine-grained soils Nebraska reported some use of plaster of paris to determine the volume of the test hole

All of the foregoing methods are destructive, that is, the material being tested for density must be removed from the roadway and then weighed. However, a number of states are investigating the use of nuclear moisture/density gauges that permit non-destructive measurements. Questionnaires and interviews indicate that approximately 25 percent of the states are making limited use of nuclear moisture/density gauges for compaction control; another 50 percent of the states are using one or more units of the equipment for nonspecification field checks on density or other experimental and research activity. Thus, a total of 75 percent of the states as of July 1964 were involved in some application of nuclear principles to moisture and density measurements

Field density is only one part of the over-all problem of compaction control. The standard maximum density of a given material must also be known if the percent compaction of the field-compacted material is to be determined. Standard Proctor, modified Proctor (AASHO designations T 99 and T 180), or slight modifications of these tests are presently used by over three-fourths of the states reporting. This determination should be made in the field on the material being compacted in the roadway, and this is done in many states. However, to save field-test time, some states send soil samples to the district or central materials laboratory for testing prior to construction. The reports of these compaction and classification tests are then sent to field inspectors who must identify these materials as they are being tested, during construction, for in-place density and relative compaction.

Ohio uses a "one-point" method and the Proctor needle which identifies the soil as belonging to a particular curve from a set of typical moisture-density curves. Full curves are run only on samples that do not fit one of the typical curves.

The California impact method (Test Method No. Calif. 216-F) is used by California and Nevada. The impact apparatus differs from the usual Proctor-type equipment although the basic principle of operation and results achieved are similar to the modified AASHO (T 180) test. In the California impact method, a soil or base sample (¾-in. maximum size) of known weight is compacted in a 3-in. diameter mold to yield a specimen 10 to 12 in. high. The sample is compacted in five equal layers with 20 blows per layer using a 10-lb tamper dropped from a height of 18 in. The final height of the specimen is measured and the density is computed from the height and weight of the sample. This procedure eliminates the need for striking off the sample at a given volume (1/30 cu ft) as is done in the AASHO procedure. In addition, the use of wet density for compaction control obviates the need for drying in-place density and compaction test samples.

Oregon uses the Harvard miniature apparatus and the Speedy moisture tester to determine the maximum dry density and optimum moisture content of soil. The test is conducted on minus No. 4 material using four layers with 25 blows per layer at a spring force of 37.5 lb. Standard density is corrected for percentage retained on the No. 4 sieve.

Mississippi and New Jersey obtain compaction control by regulating the rolling pattern and type of compaction equipment. Mississippi establishes the particular rolling pattern by checking field density against required performance. New York also specifies a required rolling pattern for granular base material without any requirement for density

The coarser-grained materials often used in base course construction are ordinarily not as moisture dependent as most natural soils, and the quality and the gradation of these materials generally is controlled at the source. Therefore, test procedures for compaction control of base construction often differ from the procedures used for soil. One method for determining standard density requires that the base material be separated on the No. 4 sieve and the AASHO (T 99 or T 180) test be performed on the minus No. 4 material. The resulting maximum dry density is then corrected for the percentage of plus No. 4 material by using a typical correction curve for the specific gravity of the stone

Some states have developed special procedures and equipment. These differ somewhat from the foregoing approach. One example of such a method that is applicable to all granular materials is that used by the State of Washington. The maximum dry densities of the minus No. 4 and the plus No. 4 material, along with the specific gravity of these materials, are used in making a density versus gradation curve. This curve is then used as a standard for compaction control of the job from which the original material was obtained. All that remains to be done by the field inspector is to determine in-place density and the percentage passing the No. 4 sieve of the material removed from the test hole.

One method of stone base compaction control is that practiced by Kentucky in which the stockpiling, quality, and blending of aggregates are controlled at the source. Gradation of the stone is checked in the stockpile prior to pug mill mixing, at which time water is added. The final field control is based on in-place density only, which is specified as 84 percent of the maximum theoretical zero void density calculated from the specific gravity of the stone. After the base is placed, gradation is not checked as long as the required in-place density is achieved. The Kentucky Highway Department engineers reason that if the compactive effort, gradation, and moisture are all correct, specified compaction will be achieved. This method eliminates the need for gradation and standard density determinations.

Some states, such as New Jersey and New York, which do not specify density for the compaction control of granular material, consider gradation to be one of the more important factors. Most other states also require gradation testing of the base material compacted in the roadway, and, in general, these tests are performed in accordance with AASHO-ASTM procedures. According to questionnaires and interviews, the complete gradation test required about 1 hr to complete in the field, but this time is shortened if the mechanical analysis is limited to selected sieve sizes.

According to AASHO-ASTM procedures, there is no specified method for determining moisture content except as part of other determinations. The usual reference specifies oven-drying at 105° C to constant weight. However, field practice is generally confined to three common methods of moisture determination. (1) flooding the sample with alcohol which is then burned off, (2) heating the sample in a frying pan over a gasoline stove or butane heater, and (3) using calcium carbide to generate gas pressure in a device such as the Speedy moisture tester. The first two methods require weighing the sample before and after heating, whereas the percentage of moisture in terms of wet weight of a pre-weighed standard size sample is read directly from the pressure gauge of the Speedy moisture tester.

The Speedy moisture tester is gaining in popularity; at present, over half of the states surveyed indicate that they make some significant use of the device. It is generally limited to moisture determinations on materials finer than a No. 4 sieve because of the relatively small sample used. Oregon uses the Speedy moisture tester on only the minus No. 4 portion of a granular base material, and corrects for the amount of moisture in the coarse fraction This correction is obtained by either field drying the plus No. 4 material or using typical values of moisture content for a saturated surface-dry condition.

Portland Cement Concrete

Test methods pertaining to control of portland cement concrete highway construction normally are used for the evaluation of compressive strength, flexural strength, air content, consistency, and cement content.

The great majority of compression tests performed on cylinders and cores are conducted in accordance with the standard AASHO-ASTM method of test. A nondestructive testing device known as the Swiss or Schmidt impact hammer is also used by a few states, but only for supplementary information.

The modulus of rupture of concrete beams is normally determined by the third-point loading method, although the center-point loading method also is frequently used.

The air content of fresh concrete is determined more often by the use of pressure meters, although the gravimetric method also is used frequently. When lightweight aggregate concrete is being tested for air content, the volumetric method (Roll-A-Meter) is usually used. The Chace air meter also is used by some states to obtain supplementary information on air content of fresh concrete.

Field determination of the cement content of fresh concrete apparently is very limited. The only test method in general use by a state highway department is the electrical conductivity method used by the State of Washington.

Time Limits for Rapid Tests

Specifications currently in use by most state highway departments require that materials be within set limits, with no provision for exceptions. It is understandable that no agency is anxious to accept any material that does not meet their quality requirements, and they impose rigid regulations to reject all units that do not meet the standard set by their specifications However, a logical analysis will show that unless an agency is willing to test *all* units it will probably accept some percentage of material or work that does not meet specifications (*176*).

An analysis of asphalt samples taken from a very closely controlled project, the AASHO test road, has shown that nearly 14 percent of these samples failed to meet specified compaction requirements (*177*). This fact, however, was noted only because of the large number of samples taken from the roadway. Routine construction control practices may not have been as informative. The knowledge that rigid "go, no-go" specifications are virtually unenforceable is making the use of statistical methods more attractive to engineering and supervisory organizations responsible for the highway construction program. Because acceptance of some fraction of substandard material is inevitable, specifications therefore should state the percentage of defective samples that will be tolerated for items of major and minor importance (*1*).

An additional item of importance is the philosophy behind the construction control testing In the past and, in many cases, at the present time, construction engineers, using judgment formulated through years of experience, maintain quality control by immediate and constant surveillance of a highway project. However, the rapid expansion of the highway program has increased the inspection requirements. The inspection team, therefore, has been supplemented with additional personnel who are perhaps more knowledgeable in the classroom sciences but are lacking experience required in the art of construction. The decisions made in the past based on "engineering judgment" must now be supplemented by objective analyses based on reliable and significant test information. In addition, new methods and advanced equipment have outdated the old rules of thumb so that the responsibility for quality control is being placed more frequently on the contractor. The function of the highway department is not to direct the contractor in the performance of his work but to accept or reject what he has produced (*178*). This is evident from the wide adoption of "end result specifications" by state highway agencies.

Rapid tests, therefore, will have a dual role· (1) quality control of production, and (2) acceptance sampling of finished products The first area is becoming more the concern of the contractor and may, in the future, be carried out by his own forces. The second role, however, remains the responsibility of the agency administrating the contract. The following discussion is, therefore, limited to acceptance testing, and a criterion for estimating reasonable time limits for rapid tests is presented on this basis.

Number of Tests Required for Construction

Materials specifications have long reflected the necessity of requiring a minimum number of tests for determining the quality of material or work to be accepted Usually the number of such tests was chosen arbitrarily. In some cases the number of tests was governed by how much time and money were available for these tests. Selection of samples was frequently conducted by dividing these tests among what the inspector considered good, average, and poor material. If statistics are to be applied correctly, then sample selection must be free of such bias; otherwise, efforts to project the attributes of the samples to the entire quantity of material will be thwarted (*177*).

The number of tests required for a meaningful statistical analysis will be influenced by the quantity of material to be accepted (lot size), the degree of confidence that the samples are truly representative of the lot, the sample size, and the variabilities of material and test method

An excellent discussion of sample size necessary to estimate the average quality of a lot or process is contained in the appendix of an ASTM publication (*179*).

Lot Size

Determination of lot size is not entirely a statistical problem, but one of economics From the statistical point of view, the lot should be fairly homogeneous so that a reasonable number of samples can accurately predict its properties. The economic factors are two-fold· (1) the contractor desires to know as soon as possible whether the work he has completed is acceptable; and (2), in the event the material is unacceptable, the lot size should be small enough so that the replacement or modification cost is not a deterrent to its rejection

Each lot depends on the type of construction and will be influenced usually by production rate, test time, and the decision time for analysis of test data. In addition, samples should be taken only after the lot has been completely produced; otherwise, the normal distribution of test results, which is generally assumed, is less likely to occur. Therefore, if one assumes a maximum delay for acceptance or rejection equal to the time required to produce one lot, the minimum lot size is given by:

$$N = PR \{\Sigma T_R + T_D\} \qquad (2)$$

in which

N = number of units in lot;
PR = production rate (units/time),
ΣT_R = total test time, and
T_D = decision time.

In this equation, the production rate usually is known, and the decision time is largely independent of the test method used. The total test time will depend on the sampling plan selected for the given material, which in turn must be selected according to the acceptable level of confidence.

Acceptance Sampling Plans

Acceptance sampling may be carried out in several ways, but two popular methods are (1) sampling by attributes (*180*) (i e., a go or no-go decision), and (2) sampling by variable (*181, 182*) where measurements are made to some accuracy. However, before any sampling plan can be carried out the consumer and the producer must agree on criteria for acceptance or rejection In addition, the sampling plan should be designed so that the confidence of rejecting substandard material and the risk of rejecting quality material are at a level that is satisfactory to both parties

From the producer's (contractor's) standpoint, the statistical sampling plan should be designed so that there will be a low risk, α, or probability of rejecting acceptable quality products. An acceptable product is defined as one having an acceptable quality level (AQL) which is the maximum percentage of defective samples that can be tolerated in calling a lot acceptable. Because statistics are involved, there can never be 100 percent certainty that a lot having AQL or better will always be recognized. Hence, the producer must accept a risk, α (usually 5 percent), that material of AQL or better will be rejected no more than α percent of the time

The consumer, on the other hand, desires a sampling plan such that material of LTFD quality (lot tolerance fraction defective), or worse, will not be accepted more than β percent (consumer's risk) of the time. Because AQL and LTFD and the risks involved are somewhat dependent on each other, some compromise must be reached by consumer and producer in selecting these limits. The magnitude of these values will depend on the material being tested and its importance in the over-all performance of the end product For example, critical materials or tests should have a smaller AQL than those that are less critical. As an illustration, the water content of a concrete batch requires far more control than, say, the gradation of the aggregate. Therefore, a study of all materials and tests is needed to determine values of AQL, α, LTFD, and β, thus establishing standards of quality and risk.

Most specifications for highway materials require that measurements of some sort be taken and recorded. For this reason, and the fact that acceptance by variables sampling plans is more efficient, these sampling plans are applicable for highway construction needs These acceptance by variables sampling plans require that the variations in materials be normally distributed, although other sampling plans could be used if the distribution is drastically different from normal.

Acceptance by variables sampling plans also require that AQL, α, LFTD, and β be specified and that the total standard deviation, σ, including material and test method, be known or can be estimated. Acceptance limits must also be specified, in some cases only a lower limit, L, is necessary whereas, in others, both an upper limit, U, and lower limit are required. These limits are used to calculate the ratio of the difference between limit and mean value of the samples to the standard deviation. This ratio is given by $(\bar{X} - L)/\sigma$, in the case of a lower limit, or $(U - \bar{X})/\sigma$, for an upper limit. These calculated values are then compared to acceptance criteria based on AQL, α, LTFD, and β. Some acceptance by variables sampling plans, such as those reported in Grant (*183*) or Duncan (*182*) and the MIL STD 414 (*181*) allow control over AQL, α, LTFD, and β; whereas, others such as the one illustrated by Shook (*177*) only allow control over AQL.

It is not the purpose of this report to discuss statistical sampling plans in detail. The selection of a plan will depend on the material or process to be sampled However, the plan of Lieberman and Resnikoff (*184*) appears particularly siutable for highway work (*177*). Their plan offers three alternates· (1) known standard deviation plans, (2) unknown standard deviation plans, and (3) average range plans Shook (*177*) provides an excellent discussion of this plan and several illustrative examples using AASHO test road data.

Variabilities

In testing a sample, three variances are present: (1) the variability of the material, σ_M; (2) the variability of the test method, σ_T; and (3) the variability of the operator, σ_O. Hence, the apparent variability, σ_A, is

$$\sigma_A{}^2 = \sigma_M{}^2 + \sigma_T{}^2 + \sigma_O{}^2 \tag{3}$$

Regardless of whether σ_M, σ_T, and σ_O are known, the apparent variability, σ_A, must be used in the sampling plan. It is, however, of interest to know what σ_T and σ_O are. This could be accomplished by experiments designed to measure these variabilities. However, operator variability is variable between operators and there is no assurance that the same variability is inherent in two pieces of identical test equipment. For these reasons it is advisable to use control charts along with acceptance sampling so that the estimate of σ_A can be made as reliable as possible as work proceeds (*185*).

Sample Size

Selection of sample size has been studied by Miller-Warden Associates (*186*). The criterion presented in their report is based on the assumption that normal distribution exists and samples are chosen at random. The sample size may then be determined by the following considerations, however, a more accurate determination of the average property of a lot can be made by averaging the mean values of sub-lots. The standard deviation of the sub-lot mean values from the over-all mean, σ_X, is related to the standard deviation of all values by:

$$\sigma_{\bar{X}}{}^2 = \sigma^2/n \tag{4}$$

in which n is the sample size. An acceptable error, Δ, by which any $\bar{X}$ of a sub-lot may deviate from the true mean is selected. Further, upper and lower limits, $\pm\lambda\sigma_{\bar{X}}$, are prescribed for any $\bar{X}$, where λ is a coefficient of confidence The wider these limits (that is, the larger the value of λ) the greater the confidence that $\bar{X}$ will fall between these limits. Table 3 gives values of λ and the probability that $\bar{X}$ will be between $\pm\lambda\sigma_X$ with respect to the absolute mean.

By varying the sample size, the measure of confidence, $\lambda\sigma_{\bar{X}}$, can be equated to the acceptable error, Δ.

Substituting $(\Delta/\lambda)^2$ for $\sigma_{\bar{X}}{}^2$ in Eq. 4 gives

$$n = \left[\frac{\lambda\sigma}{\Delta}\right]^2 \tag{5}$$

Sample size may also be determined (*179*) in terms of coefficient of variations, V.

$$n = \left[\frac{\lambda V^2}{\delta}\right] \tag{6}$$

in which

$V = 100\ \sigma/\bar{X}$, the advance estimates of the coefficient of variation, in percent;
$\delta = 100\ \Delta/\bar{X}$, the allowable sampling error, in percentage of $\bar{X}$;
$\lambda =$ a coefficient of confidence; and
$X =$ the expected mean value of the characteristic being measured.

A nomograph for determining sample size for $\lambda = 1.96$ is given in the Miller-Warden report (*186*).

The method for determining sample size just mentioned only considers α and an acceptable error and does not take into account AQL, LTFD, or β. The method that Shook (*177*) illustrates, although it allows different sample sizes, does not give any criterion for determining which sample size to use. Sample size may be obtained by using Eqs. 5 or 6 or by empirical determinations based on lot size, such as the U S. Government MIL STD 414 (*181*). In the acceptance by variables sampling plans reported in Duncan (*182*) the sample size is strictly determined by AQL, α, LTFD, and β and is independent of σ.

Maximum Test Time

After the number of tests required for accurate evaluation of acceptability of a given material or process has been determined, the maximum time for acceptance testing to keep

TABLE 3

APPROXIMATE PROBABILITY
THAT SAMPLING ERROR WILL EXCEED Δ

λ	PROBABILITY
2.96	3 in 1,000
2 58	1 in 100
1 96	1 in 20
1.64	1 in 10
1.04	3 in 10

Source. ASTM (179)

pace with construction may be calculated. The following criterion is presented:

$$T_R = \frac{1}{n}\left[\frac{1}{Q_L} - T_D\right] \qquad (7)$$

in which

T_R = maximum time for a rapid test, in hours;
Q_L = production rate, in lots per hour,
T_D = decision time required to accept or reject a lot, in hours; and
n = total number of samples required per lot.

Example 1

To illustrate the foregoing criterion consider the following case·

A contractor is placing an asphaltic pavement at the rate of 1,000 ft/hr. Final acceptance of the pavement will depend on its density after compaction. The average density is expected to be 140 pcf. From tests on preceding sections of pavement, the apparent standard deviation, σ_A, which includes variance of material, test, and operator, was approximately ± 3.5 pcf. If the acceptable error by which the mean from any sub-lot may vary from the absolute mean is 1 percent (or 1.4 pcf) then, using Eq. 5, the number of samples required is $[(1.96 \times 3.5)/1.4]^2 = 24$ tests/lot.

Specifications require that the range of densities shall not exceed ± 5 percent (± 7 pcf for this example) of the mean density, and the desired confidence is that no more than one test in twenty shall exceed these limits. From Table 3, the confidence factor, λ, necessary to provide this precision is 1.96.

Twenty-four tests per lot will produce the desired precision as long as the lot being sampled remains relatively homogeneous Should the mean values of density significantly shift up or down, then the lot should be broken into sub-lots so that homogeneity within a lot can be restored

Lot size, however, is determined largely by economic factors. Assuming that 2 hr of production is the maximum quantity desired for acceptance or rejection at any one time, the lot size is then 2,000 ft of pavement. If the decision time required for acceptance or rejection of the lot is ¼ hr and one-half lot is produced every hour, then, from Eq 7, $T_R = \frac{1}{24}(1/\frac{1}{2} - \frac{1}{4}) = 0.073$ hr/test or nearly 4½ min per test.

If no test method is available to meet the foregoing speed and accuracy requirements, adjustments must then be made in the confidence limits or lot size or both. The following example illustrates these adjustments.

Example 2

Assuming that the fastest available asphaltic concrete density test requires a test time of 15 min and identical lot sizes as in example 1 are maintained, the total number of tests is reduced to $[(1/Q_L) - T_D]/T_R = 7$ tests/lot. Using Eq 5 it is found that the confidence factor, λ, is reduced from 1.96 to $(\Delta/\sigma)\sqrt{n} = (1.4\sqrt{7})/3.5 = 1.06$. The probability that test values will exceed the desired limits rises from 1 in 20 to approximately 3 in 10.

On the other hand, if it is desired to maintain the 1 in 20 confidence level, the lot size may be increased from 2,000 ft to (Eq. 2) 1,000 [24 (¼) + ¼] = 6,250 ft. The risk of rejecting more than a mile of finished pavement must then be economically justified

An alternate solution can be obtained by increasing the number of crews and instruments performing the density tests If one test can be performed in 15 min, then it will be necessary to conduct three or four tests simultaneously to complete testing before the next lot is produced. However, the standard deviation of test results may increase or decrease under this new procedure. The number of samples required may then be recalculated, based on this new information. The sampling program will be more efficient when it uses available information concerning materials and test methods.

POTENTIAL USES OF ELECTROMAGNETIC RADIATION

A review of available literature pertaining to electromagnetic radiation was conducted to evaluate the possibility of application to highway construction materials testing.

The term spectroscopy applies broadly to any study of material using electromagnetic radiation. In terms of the original types of interaction of radiation with matter, spectroscopy may consist of a study of scattering or absorption. In these active forms, the material under study is subjected to radiation and the resulting interaction is studied, in the passive form of emission spectroscopy, the radiation coming from the excited material is studied. No information is gained from emission spectra which cannot be obtained from absorption spectra Experimental techniques and the accessibility of the sample generally dictate the choice.

The refractive index of a material is a monotonic function of density for a given chemical composition. If one uses polarized radiation of the 1-m wavelength region so that no diffraction results it should be possible to measure the refractive index of the homogeneous material. A calibration curve of density versus refractive index can be constructed which should hold for any substance of the same chemical composition. Thus, the density of certain foam plastics such as styrofoam and some synthetic ceramic materials could be obtained. For perfectly dry aggregates the same information is possibly obtainable; however, small variable amounts of water, with its high dielectric constant, will produce relatively large variations in the refractive index, hiding small variations due to density of the inorganic aggregate.

Infrared radiation may be used solely as a means of temperature determination. A material is heated uniformly on one side by a heat source which moves over the sample. After a short time, the total radiation emitted by the specimen at a given location on the other side is measured. A flaw or air void in the interior represents a blockage of heat flow and the surface immediately over the flaw is cooler. These techniques have been studied and are found to be applicable for studies of laminations, bonding, weld joints, etc; however, if the technique is to be applied to road construction, the emitted radiation must be measured from the same side as the heat source. With thick materials and infinite planar dimensions, a powerful heat source is required which makes detection difficult.

In the case of a hot-laid asphaltic concrete layer, the pavement heat loss by conduction to the subgrade and by convection and radiation from the top surface might be indicative of interior conditions; however, knowledge of the subgrade temperature and conductivity seems necessary, and this alone makes the procedure time-consuming.

Use of electromagnetic waves as tools in the area of nondestructive testing is at present restricted mostly to acceptance testing. These involve the many branches of spectroscopy and are carried out under laboratory conditions on small, specially prepared samples. Quality control testing (i.e., in-place testing of materials under field conditions) by use of electromagnetic waves is restricted almost solely to scattering of gamma rays or X-rays. This is necessarily so, because to gain knowledge of the interior requires considerable penetration by the radiation. The best-known examples are uses of gamma-ray scattering and neutron bombardment for density, moisture content, and asphalt content determinations (*97, 15*).

The main obstacle restricting extensive use of other regions of the spectrum other than X-rays or gamma rays appears to be the fact that phenomena arising in these other regions are surface effects and cannot give reliable information about the interior. This must be interpreted in terms of the primary objectives of field testing of highway construction (i.e., the determination of bulk and composite properties of soil, aggregate, and cementing materials). Gamma rays have the energy necessary for deep penetration and this ability has led to the development of the nuclear density and moisture gauge.

CHAPTER THREE

DEVELOPMENT AND EVALUATION OF RAPID TEST METHODS

ASPHALT CONTENT DETERMINATION FOR PAVING MIXTURES

Three test methods for the rapid determination of asphalt content of asphaltic paving mixtures were selected for laboratory evaluation. Two test methods, the stain method and the flask method, were not subjected to extensive evaluation because the third test, which has been designated the ignition method and was being developed concurrently, appeared to be the most practical of these methods.

Stain Method

The stain method (*16, 17*) has several limitations; these include operator technique and errors related to the amount of fines in the paving mixture. The approach taken in this study was to develop a more reliable test procedure that would minimize the variability introduced by the operator.

A first consideration was to develop a procedure that would produce duplicate stains for the same mix. The procedure finally selected was reasonably satisfactory and requires only a 6-in.-square piece of paper hand toweling, a Marshall specimen mold, and a Marshall compaction hammer. The paper toweling is secured in the bottom of the mold. Then the hot mix is spooned into the mold, and the mix is subjected to ten blows by the compaction hammer. This procedure ensured that the paper toweling would acquire a distinct stain. Examples of typical stains from an asphaltic concrete mix at various asphalt contents are shown in Figure 2. The mix consisted of 35 percent fine river sand and 65 percent crushed stone with a top size of ½ in. Other mixes were tried, with similar results.

A second consideration was to develop a practical measurement system that could be substituted for the visual evaluation of a stain by the operator. A standard light source was directed on the stain and the intensity of the reflected light was measured with a photoelectric cell (photographer's light meter).

Little correlation was found between the intensity of reflected light and the amount of asphalt in the mixes. Lack of success can be attributed to insufficient sensitivity of the photo cell and the variation in stains due to mix type. For these reasons further development of this approach was abandoned

Flask Method

The flask method (*9*) is currently used by the Wyoming State Highway Commission. Because the characteristics of this test are known, studies of this test method were limited to laboratory-made mixes.

The flask method is simple to perform and can be completed in 30 to 40 min. However, constant attention is needed to ensure complete dissolution of the asphalt by the solvent. There is also the inconvenience of thoroughly cleaning the flask after each test and there is the possibility of breaking the expensive glassware. The method is suitable for a field test and is faster than the centrifuge and reflux extraction methods.

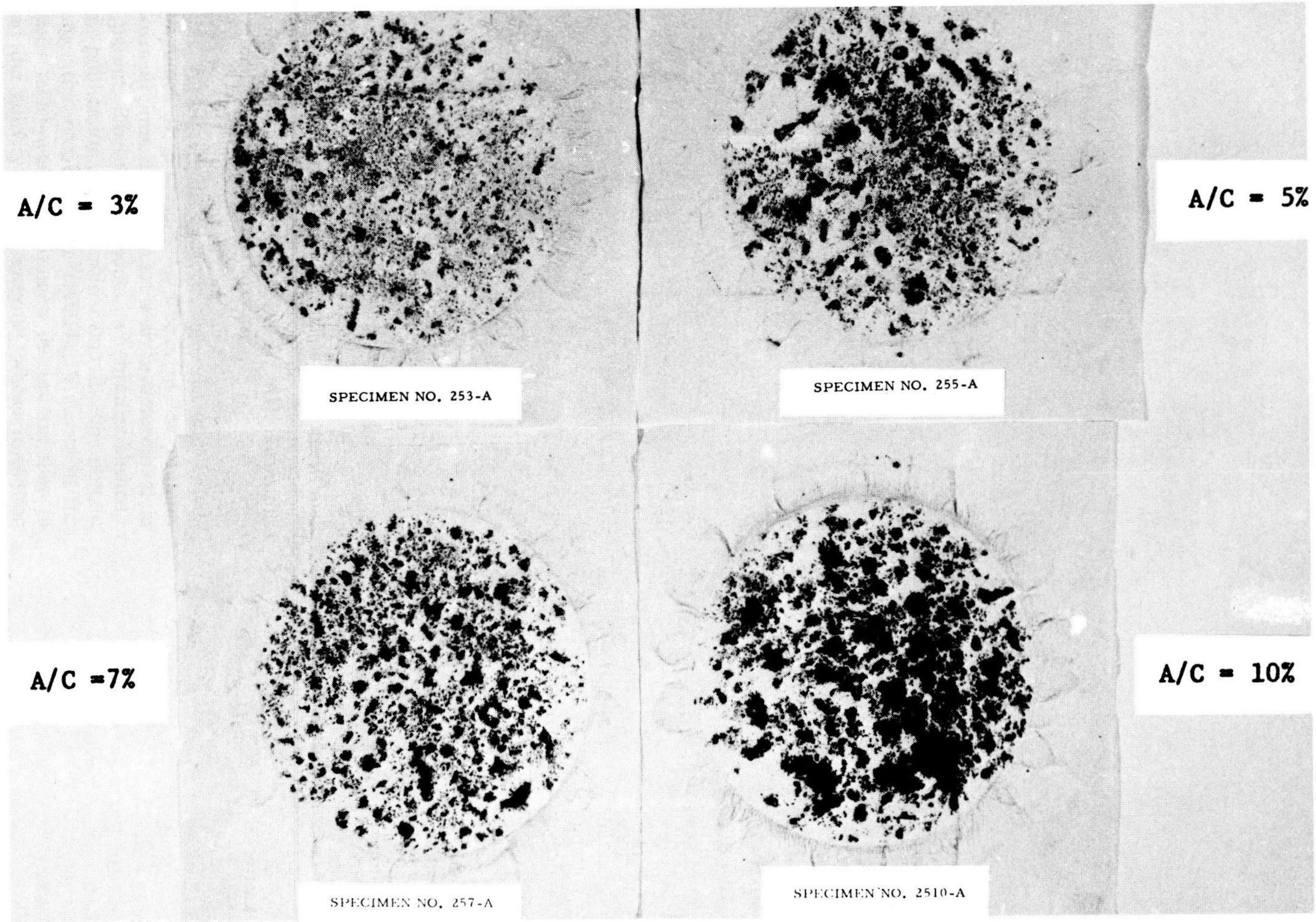


Figure 2. Stains produced by Mix A at 250° F.

Ignition Method

A test method was developed for the rapid determination of the asphalt content of a paving mixture in which the weight of a sample before and after removal of the asphalt by burning is used.

In the ignition method, virtually complete combustion of the asphalt is obtained by subjecting the paving mixture sample to a very high temperature and an excess of oxygen. The test method requires only a small amount of equipment, is suitable for field use, and does not require the constant attention of an operator while the test is in progress.

The equipment and materials required for the ignition method consist of (1) a special furnace, (2) a supply of welding-grade oxygen, (3) a supply of butane, propane, or similar gas, (4) a high-capacity balance (4½ kg) sensitive to ±0.1 gm, (5) a device to ignite the butane-oxygen mixture, and (6) a pair of thick asbestos gloves. Figure 3 shows most of the equipment in position for conducting a typical test.

Furnace

The furnace consists of three units: the lower unit or weighing pan, the middle unit or combustion chamber, and the upper unit or fines collector.

The lower unit (Fig. 4) is a steel pan that supports the sample basket and catches any material passing through the sample basket. The sample basket consists of a Monel rod frame, a No. 40 mesh Inconel wire cloth side-wall, a No. 4 mesh Inconel wire cloth bottom, and a No. 40 mesh Inconel wire cloth sub-bottom. The sub-bottom is slightly dished to ensure that material passing through the No. 4 mesh bottom will pass through the hottest zone in the combustion chamber on its way to the weighing pan.

The middle unit consists of two pieces of steel tubing. The lower piece supports two separate manifolds, one supplying butane to four nozzles and one supplying oxygen to four nozzles. Also provided in this lower piece is an opening to permit ignition of the butane and oxygen mixture. The upper piece of the combustion chamber serves as a spacer to keep the fines collector clear of the sample basket. This upper piece is provided with an opening that permits viewing of the sample while a test is in progress to

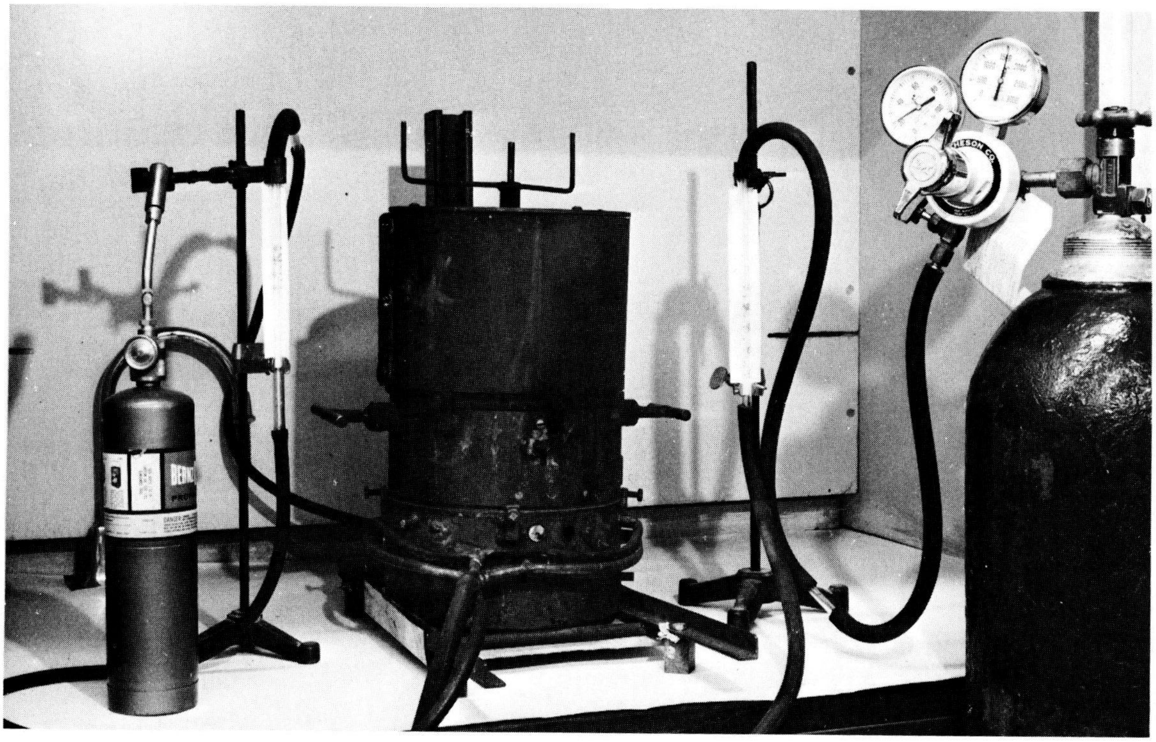


Figure 3. Ignition method equipment in position for a test.

determine when combustion of the asphalt is complete. Attached to this upper piece is a trolley unit that fits inside the vertical box member, thus enabling the combustion chamber to be raised and lowered with a minimum of difficulty.

Associated with the combustion chamber are the flow gauges used to regulate the amounts of oxygen and butane used for each test. Sensitive flow gauges were necessary because the extremely small movement of the hand-operated gas valves could not be duplicated for each test without the assistance of these gauges. Each flow gauge consists of a length of glass tubing in which is suspended a lightweight bead. The bead in the oxygen flow gauge is attached to a piece of elastic thread and the bead in the butane flow gauge is attached to the center of a hairspring.

The upper unit consists of several pieces, the collective function of which is to cool the exhaust gases, trap carbon particles carried in the exhaust gases, and return aggregate fines to the combustion chamber. Figure 5 shows the fines collector in two stages of assembly. Included in the fines collector is a combination chopper-stirrer which is used to keep the burning mixture loose in the sample basket. It is estimated that the furnace could be custom-made for less than $250.

Procedure

The weighing pan and sample basket assembly are weighed empty. A sample of paving mixture is placed in the sample basket and the assembly is weighed again to establish the weight of the mix.

Figure 4. Weighing pan and sample basket. Disassembled basket and pan with carrying frame (upper). In weighing position (lower).

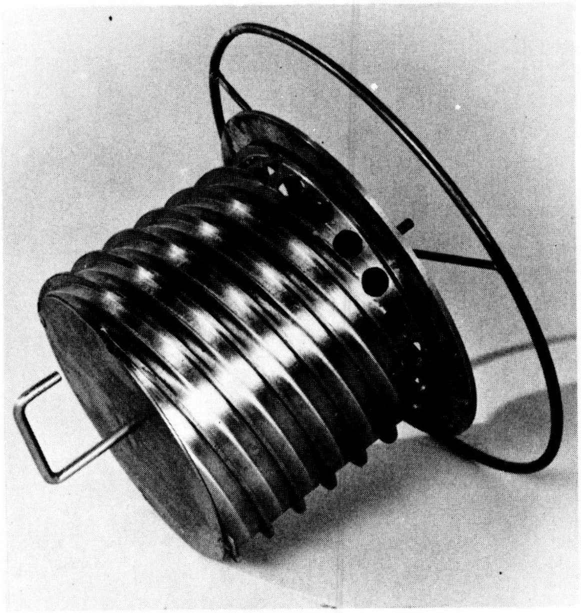


Figure 5. Details of fines collector. Innermost assembly and early version of stirrer (left). Inner cover and frame for outer cover in place (right).

After the furnace is assembled, oxygen is allowed to enter the combustion chamber; the hand torch is lit and its flame is directed through the lower opening. Then the butane is allowed to enter the combustion chamber and is ignited. (Strict adherence to this sequence will avoid explosions due to an accumulation of unburned butane in the combustion chamber.) The butane and oxygen valves are then adjusted until the flow gauges indicate that the desired amounts are being obtained. When the sample ignites, it is periodically agitated by the combination stirrer-chopper until the flames die out. At this point the oxygen and butane flows are terminated.

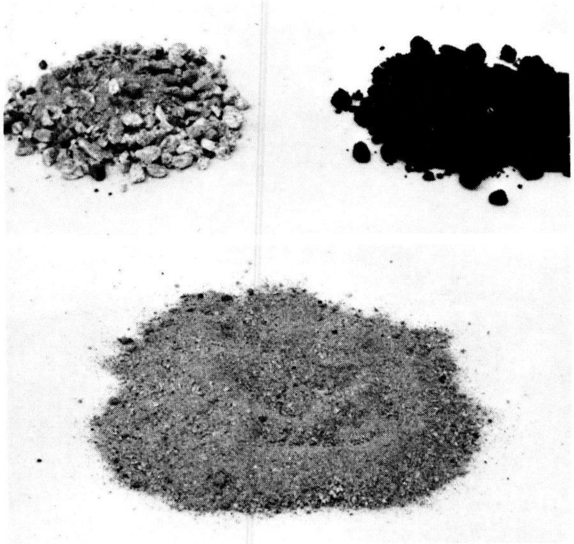


Figure 6. Asphalt mixes before and after removal of asphalt by ignition method. Binder course mix (granite-gneiss aggregate) before and after burning (upper). Sand-asphalt mix after burning (lower).

Weighings made prior to burning the sample establish the weight of the paving mixture. Similarly, final and hot tare weighings are made after the burning to establish the weight of the mixture residue. The weight loss due to burning is equal to the weight of asphalt removed by the burning plus a small loss in weight of the aggregate due to the high temperature (approx. 1,500°F) in the combustion chamber. The correction for the aggregate weight loss must be determined by burning a mix with a known asphalt content.

Figure 6 shows the appearance of two different mixes after burning. A complete burn, which is the rule rather than the exception, leaves the aggregate as clean as it was prior to making the mix.

Time per Test

The time needed to complete a test varies with the asphalt content of the mix, the temperature of the mix prior to starting the test, and the size of sample. Mixes with high asphalt contents and large sample sizes take longer to burn, and preheated mixes take less time to burn.

The asphalt content of mixes at room temperature and with normal asphalt contents can be determined in approximately 30 min; approximately 20 min of this time is the actual burning time for a 1,000-gm sample. A small earlier version of the furnace handled 200-gm samples; the test with this furnace was completed within about 12 min.

Cost per Test

The various tests conducted during the development and evaluation of the ignition method used approximately 20 cu ft of oxygen per burn and less than 1 cu ft of butane per burn. It is estimated that for 1,000-gm samples and a normal range of asphalt contents, the combined oxygen and butane cost would seldom be more than $0.20 per test.

Aggregate Weight Loss

Early work had indicated that heating the aggregate by itself in the burner did not subject the aggregate to the same conditions that prevail when burning asphalt is present. Therefore, tests to evaluate aggregate weight loss were performed on mixtures of aggregate containing 3 to 9 percent asphalt. Two series of burnings were conducted on samples prepared with 1,000 gm of graded crushed stone aggregate. One series consisted of samples prepared in the sample basket by first placing the aggregate in the basket and then pouring on a predetermined weight of asphalt. The second series consisted of samples that were mixed one at a time in a mechanical mixer.

The difference between weight loss on burning and known weight of the asphalt in the first series was assumed to be aggregate weight loss because the exact amounts of asphalt and aggregate in the sample were known. The weight discrepancy in the second series was also assumed to be aggregate weight loss. However, in this case it was necessary to calculate the amounts of asphalt and aggregate in the sample by correcting the batch weights by the amounts of asphalt and aggregate retained in the mixing bowl after discharging the mix into the sample basket

In neither case is there a distinct relationship between asphalt content and aggregate weight loss. The variability of these results is thought to be due, in part, to laboratory technique, because several different laboratory technicians conducted these tests. There is, however, a distinct difference in the average aggregate weight loss when the "pour-on" samples are compared with the "mixed" samples. The aggregate weight loss for 23 "pour-on" samples fell between 1.3 and 8.9 gm, with an average of 4.4 gm, whereas the average aggregate weight loss for 17 "mixed" samples fell between 0.4 and 13.8 gm and averaged 7.1 gm.

Aggregate Type

Burnings also were conducted to determine if certain aggregates would suffer more weight loss when subjected to high temperatures present in the combustion chamber.

A number of mixes was made and each contained the same amount of asphalt, fine aggregate, and coarse aggregate. However, the coarse aggregate in the mix was either limestone, granite-gneiss, or quartz. These mixes were burned, and an analysis of the combined data collected from these tests performed by several operators did not indicate any significant differences in aggregate weight loss for the types of aggregate tested.

The results from one series of tests on granite-gneiss and limestone, performed by one operator, indicate, that

TABLE 4

INFLUENCE OF AGGREGATE TYPE ON INDICATED ASPHALT CONTENT

ITEM	COARSE AGGREGATE TYPE: GRANITE-GNEISS	COARSE AGGREGATE TYPE: LIME-STONE
Size of mix (gm)[a]	3,493	3,505
Asphalt content based on weight loss (%)	5.4	5.9
Batched asphalt content (%)[b]	5.4	5.4

[a] Mix split into three samples prior to burning
[b] Asphalt content corrected for estimated asphalt retained in mixing equipment

there is a greater weight loss for mixes made with limestone aggregate than for mixes made with granite-gneiss aggregate. These results are given in Table 4.

Tests performed by other operators on numerous other mixes made with quartz, granite-gneiss, and limestone aggregates also suggest that there may be an aggregate weight loss that is a function of aggregate type. However, when a number of operators were used the exact magnitude of the aggregate weight loss could not be determined, and thus the weight loss difference between aggregates did not appear to be significant.

Aggregate Breakage

The possibility of aggregate breakage due to temperature-induced stresses was investigated by determining the aggregate gradation of several 1,000-gm samples before and after burning.

The laboratory phase of this part of the investigation involved three separate aggregate conditions. In the first condition, the aggregate was batched as if a mix were to be made; then a sieve analysis was conducted. In the second condition, a sieve analysis was conducted on aggregate that was batched, mixed with asphalt in the mechanical mixer, and then washed with a solvent to remove the asphalt from the mix. In the third condition, a sieve analysis was conducted after removal of the asphalt by burning. In each case mixes containing 6 percent asphalt by weight of aggregate were prepared from granite-gneiss aggregate of the same type, amount, and gradation. The results of these tests are given in Table 5. It is evident from these results that the larger sizes are degraded.

Several plant mixes of approximately 1,000 gm also were burned and sieve analyses were conducted on the aggregate residues Results of this series of tests are given in Table 6. It is evident that the larger sizes undergo some degradation.

Test Reproducibility

Two plant-made surface mixes, one plant-made binder mix, and one plant-made base mix were tested by the ignition method by several operators to determine operator and

TABLE 5

SIEVE ANALYSIS RESULTS LABORATORY MIXES[a]

SIEVE SIZE	PERCENT PASSING: AGGREGATE BLEND BEFORE MIXING WITH ASPHALT (1 SAMPLE)	AFTER MIXING AND ASPHALT EXTRACTED (AVG OF 2 SAMPLES)	AFTER BURNING (AVG OF 3 SAMPLES)
½ in	100	100	100
No 4	54 4	53 1	62 0
No 8	39 6	37 1	45 5
No. 30	18 6	17 4	22 2
No 200	3 5	3.3	3 9

[a] All aggregate from the Liberty, S C , quarry of Campbell Limestone Co

TABLE 6

SIEVE ANALYSIS RESULTS PLANT MIXES

	PERCENT PASSING				
	SURFACE MIX NO 1[a]		BINDER MIX[a]		
SIEVE SIZE	JOB MIX FORMULA	BURNED SAMPLE NO 11	JOB MIX FORMULA	BURNED SAMPLE NO 12	EXTRACTED SAMPLE
1 in	—	—	100	100	100
¾ in.	—	—	—	93	98 5
½ in.	100	100	82 6	75	75 5
⅜ in.	—	90	—	—	—
No 4	71 9	68	40 5	36	35
No 8	60 7	56	33 1	—	—
No 10	—	—	—	26	28 5
No 30	37 8	33	22 5	—	—
No 100	—	14	—	—	—
No 200	8 4	7	3.8	—	—

[a] Both mixes were produced at the Liberty, S C , plant of Sloan Construction Co , aggregate source was the Liberty, S C , quarry of Campbell Limestone Co

test variability. The results of these burnings are given in Tables 7 and 8.

A statistical analysis was performed using the data listed for Surface Mix No. 1 F-tests at an α-level of 0.05 result in the acceptance of the hypothesis that the population variances are equal, whereas t-tests at an α-level of 0.05 result in the rejection of the hypothesis that the population means are equal Hence, it can be said that the variances obtained are apparently caused by the material and the test method, whereas the differences in the mean indicated asphalt contents apparently can be attributed to the operators.

Laboratory tests performed by Operator A indicated that the aggregate does undergo a loss in weight of about the same magnitude as indicated by previous tests on laboratory mixes during the burning operation. However, those mixes tested by Operators B and C had indicated asphalt contents that differ only slightly from the job-mix asphalt content, which would account for little or no aggregate weight loss.

In summary, it can be said that there is an operator effect associated with the ignition method in its present form, and until this effect can be controlled the influence of other variables on the aggregate weight loss cannot be properly evaluated.

Summary

Tests on laboratory-made and plant-made mixes have established that the ignition method has the ability to determine from single samples the actual asphalt content of hot-mix asphaltic paving mixtures within ±1 percent without calibration for aggregate weight loss. Results indicate that asphalt content can be determined with an accuracy of ±¼ percent whenever a calibration factor for the particular operator and mix combination is applied.

TABLE 7

RESULTS OF BURNINGS MADE ON 1,000-GM PLANT-MIXED ASPHALTIC CONCRETE SAMPLES

	TOTAL WEIGHT LOSS (GM)					
	SURFACE MIX NO 1			OPERATOR A		OPERATOR B
SAMPLE NO	OPERATOR A	OPERATOR B	OPERATOR C	SURFACE MIX NO 2	BINDER MIX	BASE MIX
1	—	59 1	58.6	66 0	55 4	36 7
2	—	57.6	58.9	—	52.6	36.7
3	63 0	56 5	59.5	—	53.1	35.8
4	64 3	57 5	61 0	63 6	53 3	30.7
5	68.9	55.8	62 0	65 7	55.8	38.2
6	65 3	61.6	64 0	61 4	55 0	41.3
7	65.3	63 3	62.5	63.0	56 0	37.1
8	67.5	61 2	63.8	61.1	52 0	38.0
9	62 3	59 3	62 1	67 9	56.0	37 9
10	63 5	59.8	62 3	68.0	54.0	38 1
11	62 8	58 5	62.9	69 3	50 6	—
12	63 0	59.0	63.2	63.7	61.7	—
13	64.9	59 8	58 3	69 9	57.6	—
14	62.1	56 1	59.5	68 8	52.8	—
15	67.0			68 3	53.9	—

TABLE 8

ANALYSIS OF BURNINGS MADE ON 1,000-GM PLANT-MIXED ASPHALTIC CONCRETE SAMPLES

	SURFACE MIX NO. 1			OPERATOR A		OPERATOR B
ITEM	OPERATOR A	OPERATOR B	OPERATOR C	SURFACE MIX NO 2	BINDER MIX	BASE MIX
Avg total weight loss (gm)	64 6	58.9	61.3	65.9	54.7	37.0
Range	62.1–68.9	55.8–63.2	58.3–64.0	61.1–69 9	50.6–61.7	30.7–41.3
No. of samples tested	13	14	14	13	15	10
Std dev	2.12	2.16	2.01	3.05	2.68	2 67
Coef. of variation (%)	3 3	3.6	3.3	4.6	4.9	7.2
Indicated asphalt content (by wt. of mix) (%)	6.46	5 89	6.13	6 59	5.47	3.70
Job mix asphalt content (by wt of mix) (%)	6.0	6.0	6.0	6 1[a]	4.6[a]	3.9
Apparent aggregate contribution (%)	+0.5	−0.1	+0.1	+0.5	+0.9	−0.2

[a] Value verified by centrifuge test results.

The ignition test equipment can be used equally well in the laboratory or the field and is relatively simple to operate. The time required for one operator to complete a test on a 1,000-gm sample is approximately 30 min. No more than one demonstration was needed to acquaint operators with proper use of the equipment.

COMPACTION CONTROL OF BITUMINOUS MIXTURES

Density measurements for compaction control of bituminous mixtures can be made either nondestructively by commercially available nuclear gauges or with gravimetric or volumetric measurements on undisturbed specimens removed from the compacted pavement. The method that uses nuclear gauges has been the subject of extensive research and evaluation The following investigation, however, was directed toward developing rapid and economical methods for removing undisturbed pavement samples for conventional gravimetric and volumetric measurements.

Specimen Removal from Compacted Pavement

Specimens removed from a compacted pavement must be representative of the pavement in all respects. To accomplish this, two approaches were considered (1) "coring" by the use of a laser, and (2) separation of the specimen from the surrounding pavement by a cup made of a thermoplastic.

Laser Coring

Laser technology has increased rapidly over the past few years (*187*, *188*, *189*, *190*, *191*), and one growing application is the use of lasers for cutting or piercing various materials. The laser has demonstrated its ability to pierce firebricks and diamonds, hence, its application in removing samples from compacted bituminous pavements was considered.

Various scientists and engineers with experience in the application of lasers were consulted; they expressed the view that high-powered lasers should be capable of cutting through compacted bituminous paving mixtures without adversely affecting the asphalt-aggregate matrix adjacent to the cut, because the heat zone of a properly adjusted laser beam can be kept very small.

A 1,000-watt continuous carbon dioxide laser has been used experimentally to fracture rock (*192*) and a device of this type would have adequate power for cutting pavement samples However, at present, the use of this laser or similar device is considered to be impractical because of the large size and high cost of this type of equipment

Thermoplastic Cup

Various thermoplastics that could be used as a flexible sampling cup were investigated. It was desired that the sampling cup be rigid at room temperature but flexible and puncture-proof so that it would not restrain the contained mix during compaction for the normal range of temperatures encountered when hot mixes were placed in it.

The performance of various potentially useful thermoplastics is given in Table 9 Of these materials, polyallomer in the 5-mil thickness was found to be the most suitable. When tested with hot laboratory mixes it softened quickly and became supple, yet did not melt and was not punctured by sharp pieces of aggregate Also, this material was easily separated from the mix when the test was completed.

After considerable experimentation, a simple technique for forming the plastic film into cups was developed. The cup was formed between two inverted ⅝-qt saucepans in an oven maintained at 174°C To facilitate uniform distribution of heat during forming, a beaker mat, trimmed to fit the inside bottom of the plastic cup, was inserted between the plastic film and the inside saucepan. The time in the oven required for the forming process was precisely 6 min 10 sec.

Cup Performance

The cups were evaluated in the laboratory by the use of different types of mixes, different placement temperatures, and different compaction methods, with no difficulties or deficiencies encountered.

Evaluation of the cups under field conditions took place during the placing of 1½ in. of hot-mix plant-made asphaltic concrete surface course. The cups were placed manually immediately after passage of the paving machine by spooning out a cavity in the paving mixture, inserting the cup, and then spooning the material back in place Removal of the cup and specimen was delayed until the paving mixture cooled to about 120°F; otherwise, the specimen would deform when handled. The actual removal of the cup and specimen was accomplished by loosening and removing the paving mixture around the cup with a pickax Figure 7 shows trimmed and untrimmed plastic cups as well as "cores" after removal from the compacted paving mixture.

Locating the trimmed cups after completion of the rolling is not a problem when the trimmed height of the cup is

TABLE 9

PERFORMANCE OF VARIOUS THERMOPLASTICS

MATERIAL	PERFORMANCE AT 200° TO 300° F
Polyethylene (construction)	Considerable melting
Low-density polyethylene film, non-oriented and non-irradiated	Melts and is punctured by aggregate
Low-density polyethylene film, oriented and irradiated	Shrinks considerably immediately on contact with hot mix (lateral dimensions decrease, thickness increases)
Polypropylene (Shell general-purpose No 5820)	Does not soften enough
Butyrate (Eastman 460A)	Does not soften enough
Polyallomer (Eastman Tenite), 5 mil	Satisfactory performance
Polyallomer (Eastman Tenite), 10 mil	Thickness hinders flexibility

slightly greater than the thickness of the compacted layer. Several untrimmed cups were also placed and they apparently performed just as well as the trimmed cups.

Measurement of Density

The bulk density of specimens obtained with the plastic cup was determined by immersing the specimens in water and measuring the volume of the displaced water. These absorb water during the immersion, as is the case with most bulk-density specimens, and the usual techniques to overcome this problem such as paraffin-coating were attempted. Spray-on water repellants were used in this investigation in an attempt to reduce water absorption. However, it was found that only one of these products (3M Company's "Scotchgard" Rain and Stain Repeller for Fabrics) would not dissolve the surface of the asphaltic concrete specimens. This product, however, did not seal the larger pores and thus was only partially successful in preventing water from penetrating the specimens.

The plastic-cup method was found to be a simple, inexpensive means of removing representative specimens from compacted hot-mix asphaltic concrete. It is hypothesized that bulk-density specimens could be obtained more quickly if that portion of the pavement containing the cup is subjected to accelerated cooling by the use of dry ice. Under these conditions it is estimated that pavement density determined by the displacement method can be completed within 1 hr.

Because paving mixture temperature at time of placement is likely to vary, there is the possibility of the mixture not being hot enough to properly soften the polyallomer cup. If it is expected that such situations will occur frequently, it may be advisable to form the cup from a thermoplastic with a lower softening temperature than that for the polyallomer.

Determination of Degree of Compaction

The use of pavement permeability measurements (*31, 34, 35*) as an indication of the degree of compaction of the paving mixture was also considered and a commercial air permeability device (Asphalt Paving Meter by Soiltest, Inc.) was obtained for evaluation studies. Parking lots, driveways, streets, and an airport runway providing a variety of pavement densities and ages (freshly laid to 1 yr old), were used for the evaluation of this device.

Air permeability was found to be affected by changes in density. It was also found that air permeability values were repeatable for any given setup; however, if the device were moved to an immediately adjacent location some difference in air permeability was likely to be found.

Data from several hundred air permeability measurements confirmed (as have other investigations) that the air permeability device can be used to detect changes in pavement density as rolling progresses. Use of air permeability measurements to determine actual density is not recommended unless an elaborate calibration is carried out on the specific pavement mix. The air permeability device that was used in this study is simple to operate, and with this device an air permeability value can be obtained in less than 10 min.

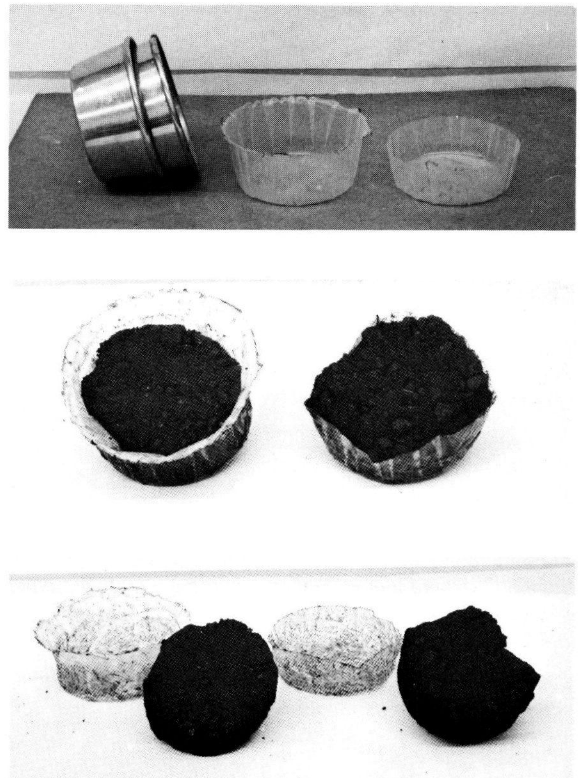


Figure 7. Plastic cups as produced and used. Cup form, finished cup as formed, and trimmed cup (upper). "Cores" as removed from pavement (center). Cups and specimens separated (lower).

GRADATION ANALYSIS OF GRANULAR MATERIALS

It is recognized that the complete sieve analysis test of granular materials is rather time-consuming and some simplification of this procedure would be desirable for field use. A laboratory study was conducted to determine whether construction control sieving procedures could be simplified by eliminating some of the sieves normally used in gradation analysis of granular materials. The elimination of some sieve sizes would reduce the time required for gradation analysis and obviate the need for sieves, sieve shakers, and other field appurtenances currently used in checking gradation specifications.

A subsidiary portion of the study was to determine what sieves could be used most effectively in estimating the amount of degradation or segregation that resulted from compactive effort applied in the laboratory.

Three aggregates of varying hardness were used in the testing program. The aggregates used, in order of decreasing hardness, were: quartz gravel, crushed limestone, and crushed granite-gneiss.

To study the changes in gradation that might be encountered in construction, 40 4,000-gm batches of each type of aggregate were prepared and then subjected to several levels of compactive effort to induce degradation. By combining the proper weights of previously separated sieve fractions the batches were prepared to conform approximately to the median gradation of the South Carolina State Highway Department *Specification 45B3-Type 1*, summarized in Table 10. To establish the initial gradation of each material as batched, 10 batches of each aggregate type were sieved and the mechanical analysis results were averaged All changes in gradation due to induced degradation then were referenced to these test results (see Table 11). Although there is some difference between the three aggregate types, the "as-batched" gradation of all types conformed closely to the specification median.

TABLE 10

SOUTH CAROLINA HIGHWAY DEPARTMENT SPECIFICATIONS FOR AGGREGATE BASE MATERIAL

	SCHD SPECIFICATION 45B3—TYPE 1	
SIEVE SIZE	RANGE	MEDIAN
2½ in.	100	100.0
2 in.	95–100	97.5
1½ in.	85–98	91.5
1 in	70–88	79 0
½ in.	40–67	53 5
No. 4	25–50	37.5
No. 8	19–42	30.5
No. 16	14–34	24.0
No 30	11–27	19.0
No. 100	4–17	10.5
No. 200	0–12	6.0

To produce degradation, an electric hammer was used to penetrate the sample in a ⅒-cu-ft bucket for approximately 10 sec. The degradation that resulted from one, two, and four penetrations was determined by averaging the results of ten tests for each of these conditions; the results are summarized in Table 11.

Figures 8, 9, and 10 show gradation changes caused by degradation expressed as percentage passing the various nominal sieve sizes. The positive variation in percentage passing that is permitted by the S.C. Highway Department specifications also is shown in Figures 8, 9, and 10.

It is evident that the greatest change in gradation takes place in the larger sieve sizes for all three types of aggregate. The amount of this change resulting from large particle breakage depends somewhat on the hardness of the rock and was greatest for the softer granite-gneiss. Other differences in the curves can be noted for the three materials. For example, the breakage of quartz gravel, amounting to approximately 7 percent within the plus ½-in. fraction, generated particles that were uniformly distributed between the ½-in. and the No. 100 sieves, with no change

TABLE 11

GRADATION CHANGE OF SOUTH CAROLINA AGGREGATE BASE MATERIALS WHEN SUBJECTED TO MECHANICAL DEGRADATION

		PERCENT PASSING (AVG OF TEN TESTS)						
			AFTER 1 PENETRATION		AFTER 2 PENETRATIONS		AFTER 4 PENETRATIONS	
BASE MATERIAL	SIEVE SIZE	AS BATCHED	FINAL	CHANGE	FINAL	CHANGE	FINAL	CHANGE
Quartz gravel [a]	2 in.	100.0	100.0	0	100.0	0	100.0	0
	1 in.	81.0	82.1	+1 1	84.2	+3.2	86.5	+5.5
	½ in.	54.6	56.0	+1.4	58 8	+4.2	61.7	+7 1
	No. 4	38.8	40.1	+1.3	41.5	+2.7	43.1	+4.3
	No. 16	24.8	25.8	+1.0	26.5	+1.7	27.4	+2.6
	No 30	19.6	20.4	+0.8	20.5	+0 9	21.1	+1.5
	No. 100	10.5	10.9	+0.4	10.5	0	10.2	−0.3
Crushed limestone [b]	2 in.	100 0	100 0	0	100.0	0	100.0	0
	1 in.	79.4	81.1	+1 7	84 4	+5.0	85.3	+5.9
	½ in.	54.5	56.8	+2.3	58.8	+4.3	60.0	+5.5
	No. 4	38.5	40.2	+1.7	41.4	+2.9	42.8	+4.3
	No. 16	24.5	25 6	+1.1	26.5	+2.0	27.8	+3.3
	No. 30	19 5	20 6	+1 1	21 4	+1.9	22.4	+2.9
	No. 100	10.4	11.8	+1.4	12 2	+1.8	12.7	+2.3
Crushed granite-gneiss [c]	2 in	100.0	100.0	0	100 0	0	100.0	0
	1 in.	79.7	82.7	+3.0	85.8	+6.1	89.3	+9.6
	½ in.	54.3	56 4	+2.1	58.4	+4.1	62.5	+8.2
	No 4	38.4	40.0	+1 6	41.3	+2.9	44 3	+5.9
	No. 16	25 1	26.3	+1.2	27 9	+2.8	30.6	+5.5
	No. 30	19.6	20.8	+1.2	22 1	+2.5	24.0	+4.4
	No. 100	10.4	10.8	+0.4	11.3	+0.9	12.1	+1.7

[a] Source Becker County Sand and Gravel Co, Cheraw, S C
[b] Source Campbell Limestone Co, Blacksburg, S C, quarry
[c] Source· Campbell Limestone Co, Liberty, S C, quarry

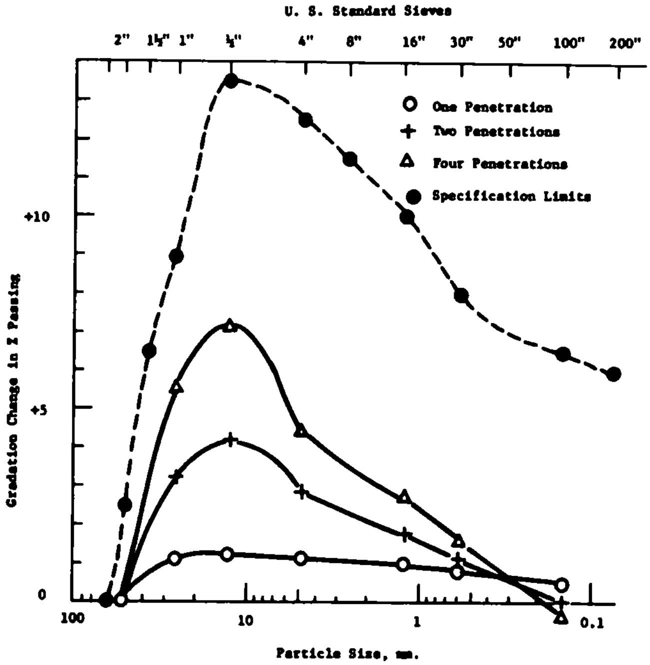


Figure 8 Degradation versus particle size for quartz gravel

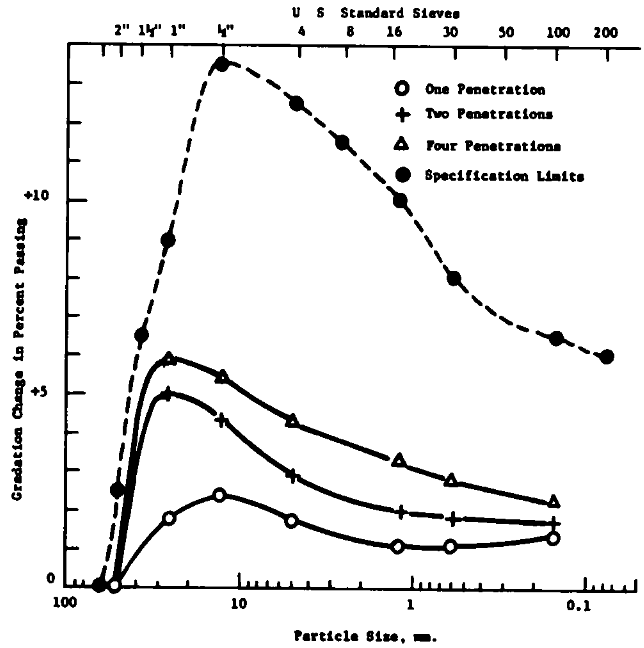


Figure 9. Degradation versus particle size for crushed limestone.

in the percentage passing the No. 100 sieve. In the case of crushed limestone, only about 6 percent breakage occurred in the plus ½-in. fraction but the breakage generated finer particles that increased the material passing the No. 100 sieve by 2.3 percent. The crushed granite-gneiss had 9.6 percent breakage in the plus 1-in. fraction but the increase in material passing the No. 100 sieve was only 1.7 percent, or a little less than for limestone. For granite-gneiss, the greatest increase in smaller material generated from the breakage fell in the No. 30 to No. 100 fraction.

It can be seen that specification tolerance is higher for the larger sieve sizes and gradually decreases to smaller amounts for the finer sieves. This is similar in shape to the actual degradation curves for the materials tested except that the allowable tolerance for the smaller sieve sizes does not drop off as rapidly as the actual degradation curves. Thus, the only violation of specifications noted for the materials tested occurred in the percentage passing the 1-in sieve for granite-gneiss.

If the gap sieving principle is to be applied to the problem of detecting potential violation of the gradation specifications, then the split of the material should be made on the particular sieve that experience indicates is most likely to be outside the limits. In the case of the granite-gneiss, the single sieve split should be made on the 1-in. sieve. For this material, the change in the percentage passing the ½-in. sieve is almost as high as for the 1-in. sieve, but the ½-in. point is well within specification limits because of the greater tolerance permitted for this sieve size.

Some engineers may feel that the percentage passing the No. 100 or No. 200 sieve is the most significant gradation parameter for granular material even though many state highway gradation specifications allow relatively wide tolerance limits for these sieves in terms of the relatively small amount of fine material present in a properly graded granular material. If, in fact, the specification limits are too tolerant of the percentage passing the fine sieves, then the solution of this problem lies in the revision of the gradation specifications to reduce the permissible percentage

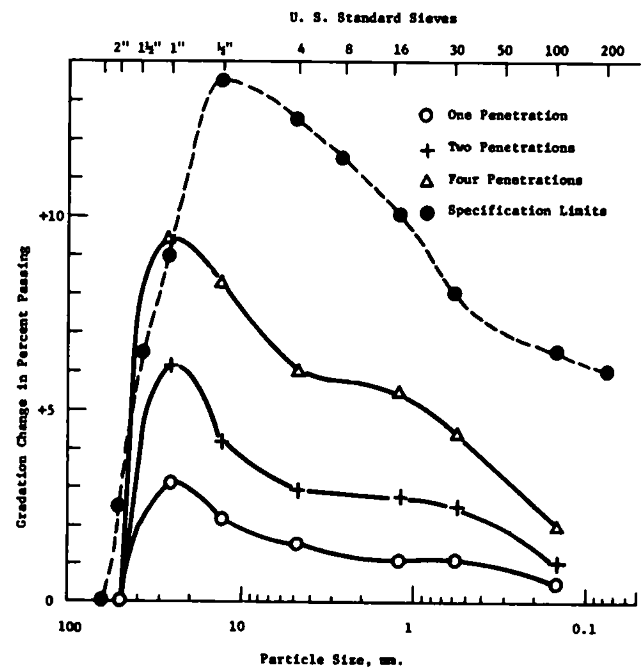


Figure 10. Degradation versus particle size for crushed granite-gneiss

passing these sieves. If the tolerance limits in this area are reduced, the necessity of splitting the sample on one of the finer sieves to detect gradation violations becomes more probable. However, it should be pointed out that if a fine sieve is to be used to split the sample, one or more coarser sieves should also be nested with the fine sieve to prevent the weight of coarse material from damaging the fine sieve. The material retained on the coarser sieves need not be weighed if the primary concern is for the percentage passing the fine sieve.

The purpose of the degradation study was to show the distribution of changes in gradation caused by compaction and how these changes can be detected by the use of a single sieve. Examination of gradation curves from this and other studies shows that, in the vast majority of cases, gradation curves that are smooth before compaction are also smooth curves after degradation. Thus, two or three sieves distributed over the grain-size range are all that should be needed to evaluate the gradation of the granular material in the field. A single sieve can then be selected that will measure the critical area of the gradation.

In summary, the application of the gap sieving principle should be correlated with (1) amount and particle size associated with greatest amount of degradation, (2) gradation of material established at the source, and (3) the permissible change in gradation allowed by the specification limits. When the sieve size has been selected to sense the potential violation of specifications that is most likely to occur, it should be possible to detect the material on the job which is suspect by using a split of the material on the one critical sieve only. When the split on the one sieve shows approaching violation of the specifications, this material should be checked by a complete mechanical analysis.

Figure 11. Coring device used in conjunction with Rainhart volumeter for density tests on soils and granular bases.

DENSITY OF SOILS AND BASE COURSE MATERIALS

With the exception of nuclear techniques, methods for density determination have undergone little development since the introduction of the sand-cone and water-balloon procedures. The accuracy and precision of these methods have been well established (*193*) and have somewhat set a standard for any new development.

The rapidity of any new test procedure may be evaluated by a comparison to the testing time required for "conventional" test methods. A technique using a coring device that substantially reduces the testing time required for density measurements with a water-balloon apparatus (Rainhart volumeter) has been recently recommended (*194*). This device consists of an electric impact hammer (Skil Roto-hammer, model No. 736), a 3½-in. carbide-tipped core barrel, and a coring guide (Fig. 11). The use of a second base plate for the water-balloon apparatus also increases the efficiency of the test procedure when two technicians are employed to perform the density tests. While one technician operates the balloon apparatus, the other technician, using the coring device and auxiliary base plate, prepares the next test site. In this manner testing time per test performed is reduced nearly 50 percent to approximately 15 min for wet density determination.

Therefore, the speed, accuracy, and convenience of any rapid test must surpass that which is currently available to assure its eventual adoption.

The Proctor needle, the North Dakota cone, and various drop-hammer penetrometers can be used to rapidly measure the strength of soil. It has been noted by Steffens and Ring (*84*) that the penetration resistance of a compacted soil is a function of the moisture content of the molded sample, and this relationship is the basis for the "one-point" Proctor method of determining the standard density. However, for a given moisture content, there is reason to believe that the penetration resistance of a particular soil is related to the compacted density.

Drop-Hammer Penetrometer

To explore the relationship between density and penetration resistance, Gioiosa (*195*) designed a drop-hammer penetrometer that was evaluated on crushed granite-gneiss base material. This penetrometer, shown in Figure 12, was also calibrated on a variety of South Carolina soils. The penetrometer needle consisted of a 9/16-in.-diameter steel rod with a 5/8-in.-diameter hardened, bullet-shaped tip capable of breaking and penetrating rock base material. The impact energy could be varied by a choice of either the 5-lb or the 10-lb drop weight. The height of the drop also was adjustable. Up to four surcharge weights, each weighing 35.2 lb, were used with the penetrometer to increase the bearing capacity of granular material at the surface of the penetration zone. A layered disk of plywood and foam rubber 7 in. in diameter and 1 in thick was placed between the soil or crushed stone and the penetrometer base so that the surcharge weight would be uniformly transmitted to the surface The penetrometer needle passes freely through a hole in the center of the disk A carriage assembly was added for mobility Figure 13 shows the complete penetrometer in operation.

Sample Preparation and Test Procedure

Laboratory evaluation of the drop-hammer penetrometer used sandy soils which, except for the micaceous silty sand, could be used as base or subbase materials. Type 1 crushed granite-gneiss macadam base material meeting the specifications (*196*) summarized in Table 10 was also used to evaluate the penetrometer Table 12 summarizes the compaction properties and AASHO classification of the soils used in this study.

Each of the soils used in the laboratory tests was compacted in a 1-cu-ft aluminum mold, approximately 8 in deep, at various moisture contents ranging from about 0 to 20 percent. Each sample was compacted as uniformly as possible using various compactive methods ranging from hand tamping to vibratory compaction with a steel plate and electric hammer. Highest densities were obtained by hand tamping with the steel Proctor tamping hammer.

Penetrometer tests on both soil and crushed stone were performed in the same manner, except that tests on the soil samples used a 5-lb hammer dropped 12 in along with two surcharge weights to provide 321 psf surcharge pressure, whereas tests on the crushed stone used a 10-lb hammer dropped 18 in along with four surcharge weights to provide 584 psf surcharge pressure.

After the sample was compacted, the penetrometer apparatus with surcharge weights was placed on the surface of the sample about 2 in. from the center. The hammer was dropped until the needle had penetrated approximately 2 in, this depth reading was recorded as the initial penetration. Additional standard blows were delivered until the penetrometer needle had penetrated to a total depth of approximately 6 in. This depth reading was recorded as the final penetration, the number of blows required to drive the needle from 2 to 6 in. also was recorded. The penetration resistance, N, was then calculated as follows:

$$N = \frac{\text{number of blows}}{\text{final reading} - \text{initial reading}} \tag{8}$$

After the first test was completed the apparatus was moved a few inches to another undisturbed spot about the same distance from the center of the same sample and the test was repeated in the same manner. The time required to obtain the two penetrations was generally less than 5 minutes for all soil types tested. The averages of the two

TABLE 12

PROPERTIES OF SOILS USED TO EVALUATE THE DROP-HAMMER PENETROMETER

SOIL TYPE	AASHO T-99 COMPACTION TEST RESULTS MAX DRY DENSITY (PCF)	OPT MOISTURE (%)	AASHO CLASS
Red sand-clay	116 0	12 4	A-2-4
Clayey topsoil	116.3	15.8	A-2-6
Sandy topsoil	122.0	13.0	A-2-4
Sand-clay mixture (85% sand, 15% clay)	120 5	12 0	A-2-6
Micaceous silty sand	111.5	13.8	A-2-4

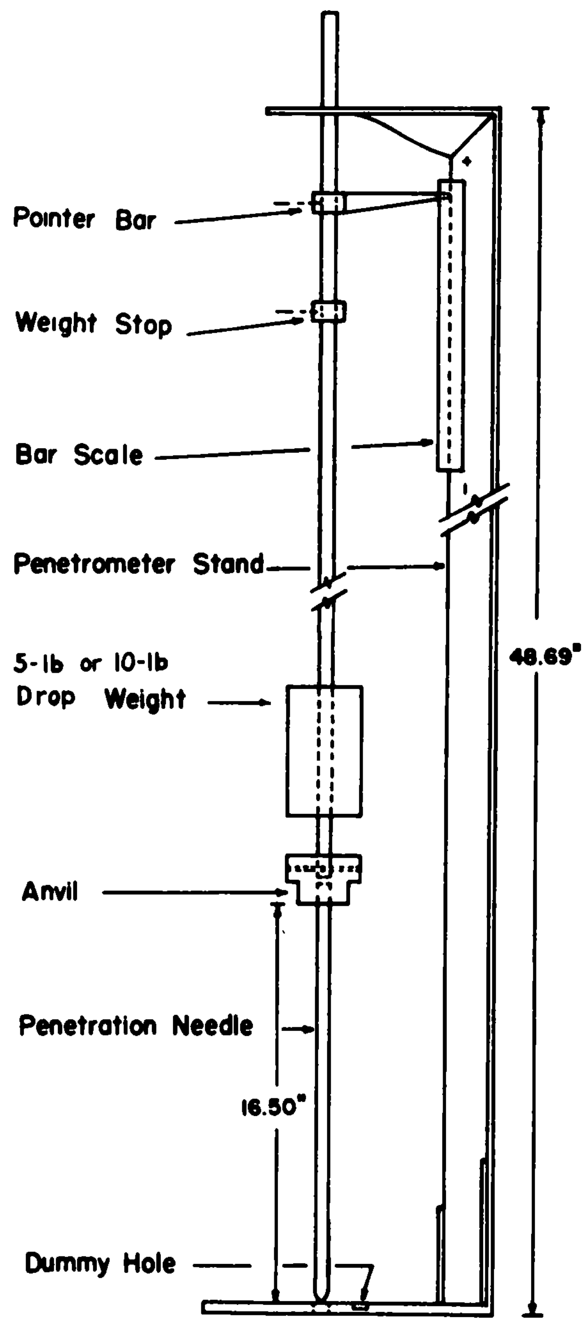


Figure 12 Penetrometer

Figure 13. Penetrometer in test position.

test results for each sample are given in Tables 13 and 14. The moisture contents of the samples at the time of the test also are given.

Calibration Procedure

Tables 13 and 14 give the observed density that was obtained from the weight of the sample in the 1-cu-ft box and the moisture content. Calculated densities that were obtained from the calibration procedure developed from the following analysis of data also are included in these tables.

Although penetration resistance, N, was greatly influenced by molding water content, it was found that, for a given moisture content, a straight-line relationship existed between dry density and the log of the penetration resistance for all laboratory calibration tests. This semi-log relationship is shown in Figures 14 through 19. The straight regression lines that best fit the data points at approximately 5, 10, 15, and 20 percent moisture are plotted on Figures 14 through 18. Figure 19 also shows several regression lines for data on crushed granite-gneiss, but for lower moisture content increments.

The general equation for the straight regression line of the semi-log plot can be expressed in the following form:

$$\gamma = A + B \log N \qquad (9)$$

in which

γ = soil dry density, pcf;
N = penetration resistance, blows/in.;
A = intercept (dry density at 1 blow/in. penetration resistance); and
B = slope (change in dry density for a 10:1 change in penetration resistance).

For all soils tested it can be noted that the slope of the regression line increases with moisture content, whereas the intercept of the regression line is higher at low moisture content, reaches a minimum at about 75 percent of optimum moisture, and then increases again at higher moisture levels. The slope and intercept of the regression lines versus molding water content, w, for each type of soil were plotted and smooth curves were connected between these points. These curves, shown in Figures 20 through 24, show the slope function as a solid line; the intercept function is shown as a dashed line. Using the values of slope and intercept interpolated from the appropriate curve at the particular moisture content of a given soil sample, along with the penetration resistance of the sample, the dry density of the soil sample was calculated from Eq. 9. The dry density for all 64 soil samples tested was calculated in this manner; these results are summarized in Table 13.

For all but the clayey topsoil, it was found that the slope and intercept functions can be expressed by second-degree equations. Although the constants for these equations vary with the soil type, these parabolic relationships, where they exist, can then be substituted in Eq. 9 to obtain a calibration equation for a specific soil type, as follows:

$$\gamma = a + b(w - w_1)^2 + (c + dw^2) \log N \qquad (10)$$

in which

γ = soil dry density, pcf;
N = penetration resistance, blows/in.;
w = molding water content, percent;
w_1 = percentage molding water at minimum value of intercept (approximately 75 percent of optimum moisture);
a = minimum value of intercept at moisture content, w_1;
b = constant of the intercept function parabola;
c = slope of Eq. 9 at $w = 0$; and
d = constant of the slope function parabola.

Table 15 gives the various coefficients for Eq. 10 that are applicable to four of the five soil types tested.

Calibration of the penetrometer with crushed granite-gneiss was in some ways less difficult than with soil because the range of molding water content was lower and had less effect on the results. The same linear relationship between dry density and log of the penetration resistance found for soils was also applicable to the crushed rock. However, the slope of the regression line showed no significant change as the molding water content was increased from approximately 1 percent to about 7 percent. The highest value of molding water content was slightly over optimum moisture for the material and about as high as could be obtained in the compaction of the laboratory calibration samples. As in the case of soils, there was a noticeable change in the intercept of the regression line as

TABLE 13

SUMMARY OF DROP-HAMMER PENETROMETER CALIBRATION RESULTS FOR VARIOUS SOILS

SOIL TYPE	OBSERVED DRY DENSITY (PCF)	MOISTURE CONTENT (%)	PENETRATION RESISTANCE (BLOWS [a]/IN.)	CALCULATED DRY DENSITY (pcf)	ERROR (pcf)
Red sand-clay	90.0	5.6	1.09	89 5	+0.5
	94 7	5.6	2.28	94.3	−0.4
	80.5	9.8	0.52	78.0	−2.5
	85.1	9.8	0.96	85.1	0
	94.7	9.8	2 43	95.9	+1.2
	102.1	9.8	4.18	102.2	+0.1
	112.0	9.8	10.82	113.3	+1.3
	93.2	14.2	1.18	93.6	+0.4
	103.2	14.2	1.91	103.1	−0.1
	113.4	14.2	3.20	113.2	−0.2
Clayey topsoil	90.1	5.5	1.15	90.8	+0.7
	93.7	5.6	2 08	93.8	+0.1
	96 7	5.3	2 88	96.1	−0.6
	81.5	10 4	0 97	81.6	+0.1
	82.1	10 1	0.81	80.7	−1.4
	89 4	10.1	2.67	90.0	+0.6
	99.8	10.2	10.32	100.7	+0.9
	72.9	15.5	0.81	72.9	0
	85.6	14.2	2.11	85.9	+0.3
	92 7	15.5	3.42	94.6	+1.9
	103 0	15.5	6.31	103.4	+0.4
	112.4	15.5	7.37	106.2	−6.2
	95 3	20.7	0.54	95.6	+0.3
	102 8	19.6	0.89	101 5	−1.3
	106.2	20.5	0.88	107.8	+1.6
Sandy topsoil	95.8	5 4	1.25	93 8	−2 0
	102.0	4.5	2.07	98.1	−3.9
	105 0	5.8	5.50	102.0	−3.0
	81.0	9.8	0.57	80.1	−0.9
	86.4	10 0	0 98	85 8	−0 6
	101.2	10.0	4.19	103 1	+1.9
	108.1	10.1	6.28	107.9	−0.2
	111.7	10.2	8.62	112.3	−0.6
	86.4	15.7	0.80	93.3	+6.9
	97.3	15 0	1.15	98.9	+1.6
	109 3	15 2	2.07	113.0	+3.7
	115.9	15.7	1.78	112.3	−3.6
Sand-clay mixture	92.1	4.9	0.85	92.4	+0.3
	96.3	4.9	2.02	98.4	+2.1
	100 2	4.8	2.48	99.8	−0.4
	103.0	4.9	3.20	102.1	−0.9
	92 6	9.8	1.17	92.6	0
	99.4	10.2	2.81	101.2	+1.8
	105.0	9.8	3.52	103.0	−2.0
	109.4	10.6	5.43	108.3	−1.1
	102 1	15.1	1.44	101.7	−0.4
	109.2	14.5	2.59	108.2	−1.0
Micaceous silty sand	77.3	5.4	0.48	76.6	−0.7
	79.7	5.4	0.90	81.7	+2.0
	84.5	5.2	0.72	80.1	−4.4
	92.5	5.4	4.16	94.0	+1.5
	76.0	10.5	0.56	74.3	−1.7
	78 9	10.3	0.95	79.5	+0.6
	87.9	10.2	3.29	91.5	+3.6
	99.4	10.2	5.58	96.8	−2.6
	82 2	15.0	0.93	81.4	−0.8
	88.2	14.2	1.92	89.6	+1.4
	95.3	15.0	4.90	102.2	+6 9
	109.5	15.5	7.35	108.6	−0.9
	85.0	20.4	0.66	83.7	−1.3
	87.8	20.2	0.85	87.6	−0.2
	95.8	20.3	1.74	100.3	+4.5
	99.9	20.3	2.04	102.5	+2.6
	105.9	20.3	2.29	104.4	−1.5

[a] 5-lb hammer dropped 12 in

molding water content was changed. This is shown in Figure 19 which shows the regression lines for 1, 3.5, and 6 percent molding water. Within this range, the influence of molding water content on the intercept appeared to be linear and the calibration equation for crushed granite-gneiss can be expressed as follows

$$\gamma = 116.7 - 0.90\, w + 27.3 \log N \qquad (11)$$

in which

γ = crushed rock dry density, pcf,
N = penetration resistance, blows/in.; and
w = molding water content, percent.

The results of 34 tests given in Table 14 were calculated for crushed granite-gneiss using Eq. 11.

Good correlation was obtained between observed dry density of the calibration samples and predicted dry density calculated from the penetration resistance and molding moisture content using the calibration procedure just outlined. Table 16 gives the coefficient of correlation as well as the standard error obtained for all of the soil and granite-gneiss samples used in the laboratory calibration of the penetrometer.

Practical Applications of the Drop-Hammer Penetrometer

Penetrometers of various types have been used successfully to measure the strength parameters of soil under field conditions existing at the time of testing. However, the split spoon sampler is the only device that has found general use in determining relative density of soils, and this application has been confined to subsurface exploration studies for the purposes of foundation design. The use of penetrometers to measure the density of soil in embankments has heretofore been avoided because of the significant influence of moisture content on the strength (and penetration resistance) of the compacted fill. However, an analysis of the results obtained in this investigation shows that the influence of moisture content on the soils tested could be evaluated, and thus a relationship was developed that would yield dry density from the penetration resistance and moisture content of the soil sample.

The speed and accuracy of the penetration test developed in this investigation is a strong inducement to further investigate the performance of the drop-hammer penetrometer under actual field conditions. In any field application, each soil type being compacted would have to be calibrated for its moisture sensitivity and penetration resistance characteristics. This would require a minimum of six tests—

TABLE 14

SUMMARY OF DROP-HAMMER PENETROMETER CALIBRATION RESULTS FOR CRUSHED GRANITE-GNEISS (TYPE I)

OBSERVED DRY DENSITY (PCF)	MOISTURE CONTENT (%)	PENETRATION RESISTANCE (BLOWS[a]/IN.)	CALCULATED DRY DENSITY (PCF)	ERROR (PCF)
119.9	1.5	1.33	118.7	−1.2
121.4	1.5	1.58	120.7	−0.7
124.5	2.0	2.62	126.3	+1.8
125.5	1.0	2.02	124.1	−1.4
127.1	1.7	2.86	127.7	+0.6
131.1	0.8	3.58	131.0	−0.1
133.1	0.7	3.99	132.5	−0.6
133.7	0.4	4.56	134.3	+0.6
134.1	0.2	4.64	134.7	+0.6
135.4	0.2	5.01	135.6	+0.2
136.1	0.2	5.76	137.0	+0.9
115.5	3.4	0.87	112.0	−3.5
115.9	3.5	1.10	114.6	−1.3
116.0	2.5	1.26	117.2	+1.2
116.2	4.1	1.74	119.6	+3.3
118.2	2.9	1.46	118.6	+0.4
119.3	4.0	1.78	119.9	+0.6
121.5	3.2	2.39	123.6	+2.1
122.4	2.5	1.86	121.8	−0.6
125.0	3.2	2.24	123.4	−1.6
125.2	2.1	2.54	125.9	+0.7
129.9	2.9	3.97	130.4	+0.5
130.8	2.8	5.26	133.9	+3.1
131.2	2.2	6.50	136.9	+5.7
132.2	4.7	5.26	132.2	−0.1
132.7	4.3	6.43	134.7	+2.0
133.7	3.1	3.48	128.7	−5.0
135.8	4.2	4.19	129.9	−5.9
118.3	5.2	1.81	119.0	+0.7
128.0	7.6	3.82	125.8	−2.2
132.2	5.3	7.11	135.1	+2.9
132.2	6.6	5.77	131.6	−0.6
134.2	6.6	6.74	133.4	−0.8
134.3	6.0	6.29	133.1	−1.2

[a] 10-lb hammer dropped 18 in.

TABLE 15

COEFFICIENTS FOR EQ. 10 FOR FOUR SOIL TYPES

SOIL TYPE	EQUATION COEFFICIENT a	b	c	d	w_1
Red sand-clay	85.5	0.20	10	0.175	9.3
Sandy topsoil	86.0	0.35	8	0.190	9.7
Sand-clay mixture	91.0	0.15	14	0.080	9.0
Micaceous silty sand	80.0	0.105	17	0.053	10.3

TABLE 16

COEFFICIENT OF CORRELATION AND STANDARD ERROR BETWEEN OBSERVED AND CALCULATED DRY DENSITY

SOIL TYPE	COEF. OF CORR.	STANDARD ERROR (PCF)
Red sand-clay	0.995	1.1
Clayey topsoil	0.980	1.9
Sandy topsoil	0.957	3.2
Sand-clay mixture	0.977	1.3
Micaceous silty sand	0.958	2.9
Crushed granite-gneiss	0.945	2.2

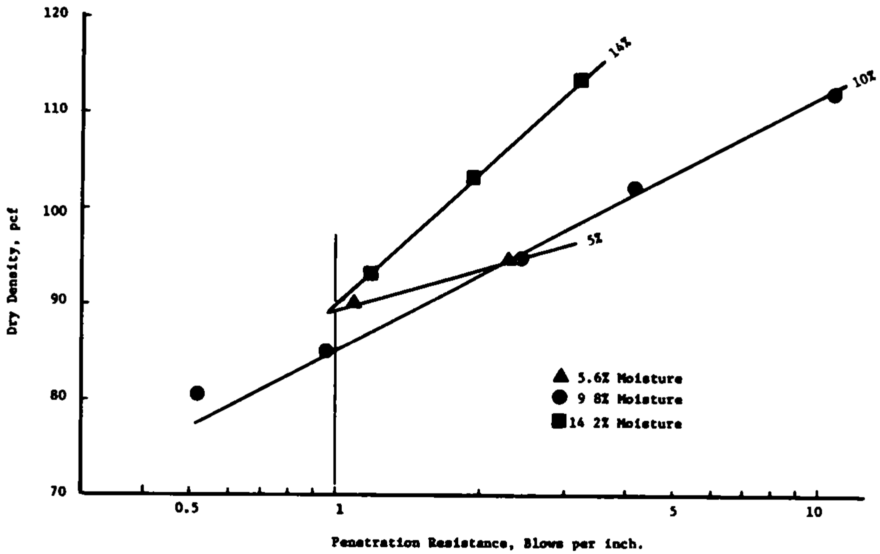


Figure 14 Dry density versus penetration resistance for red sand-clay

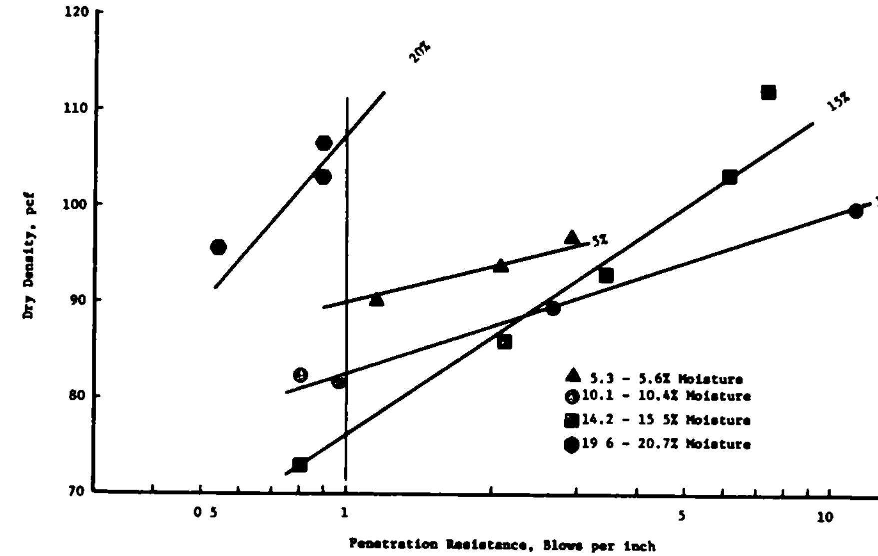


Figure 15 Dry density versus penetration resistance for clayey topsoil

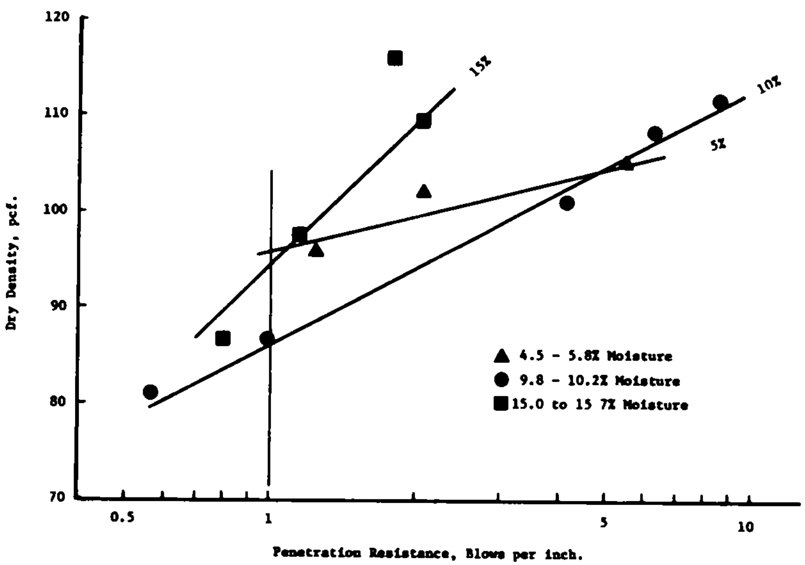


Figure 16. Dry density versus penetration resistance for sandy topsoil

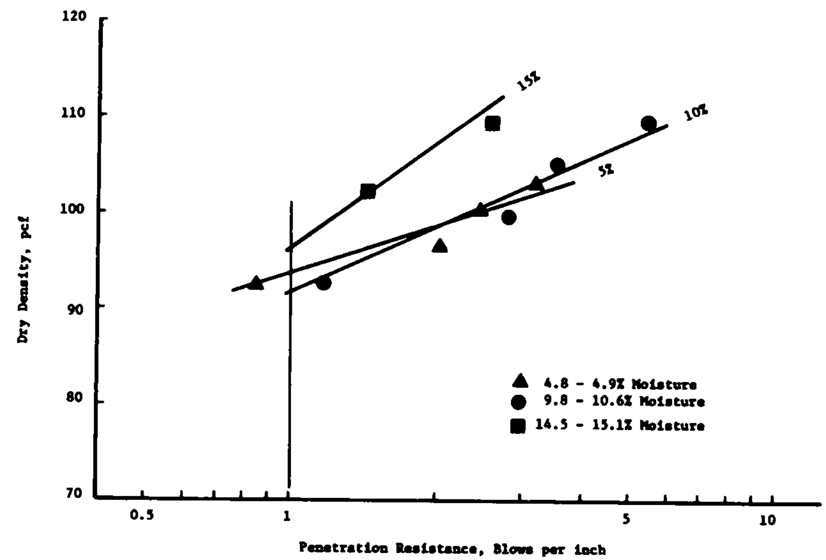


Figure 17. Dry density versus penetration resistance for sand-clay mixture

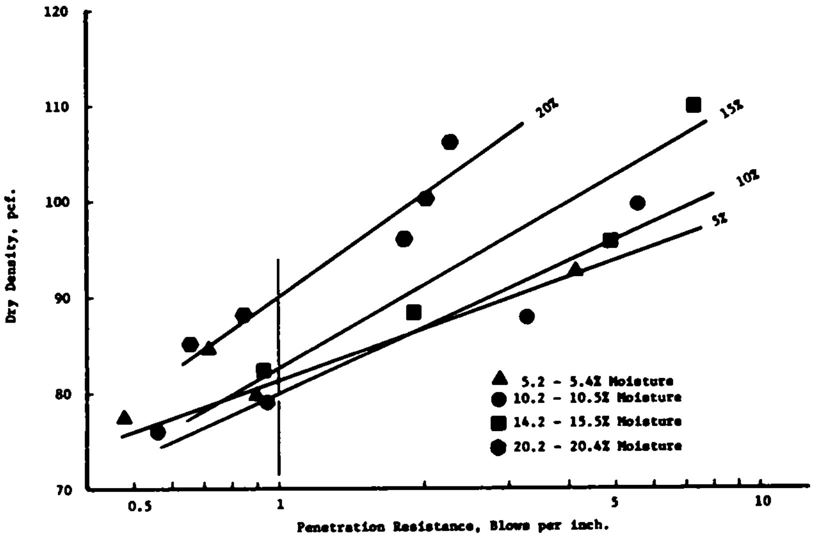


Figure 18 Dry density versus penetration resistance for micaceous silty sand

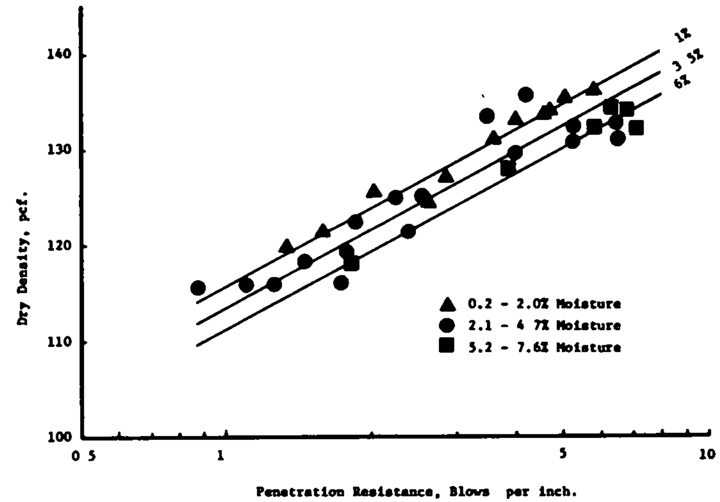


Figure 19 Dry density versus penetration resistance for Type 1 crushed granite-gneiss

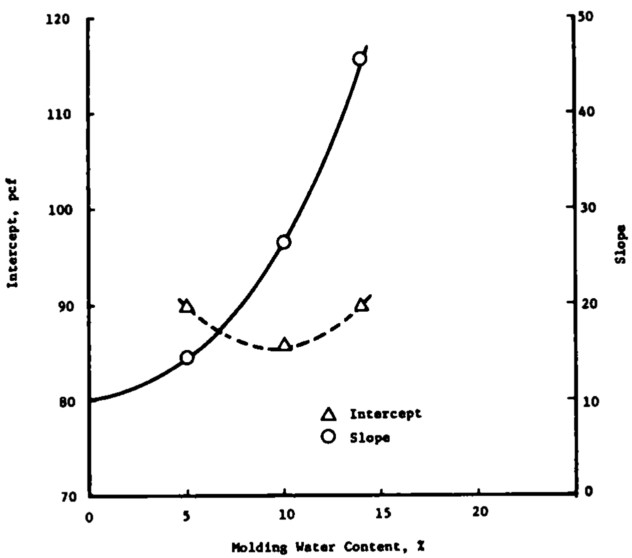


Figure 20 Intercept and slope (Eq 9) versus molding water content for red sand-clay

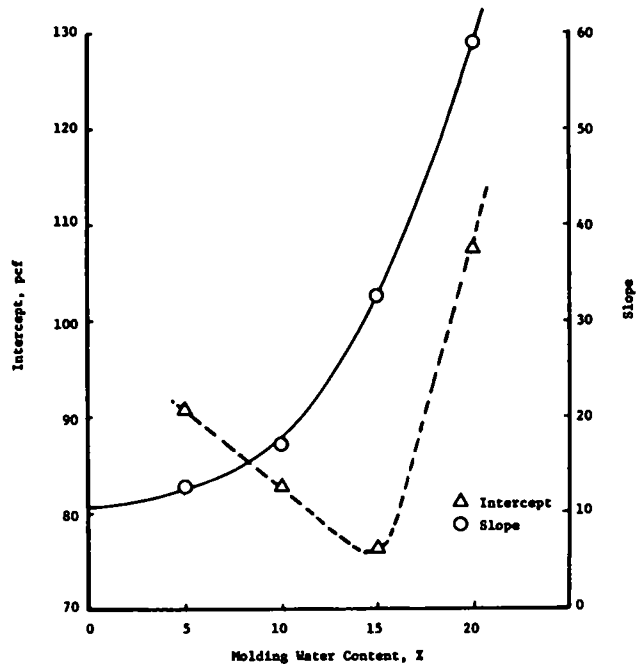


Figure 21. Intercept and slope (Eq. 9) versus molding water content for clayey topsoil

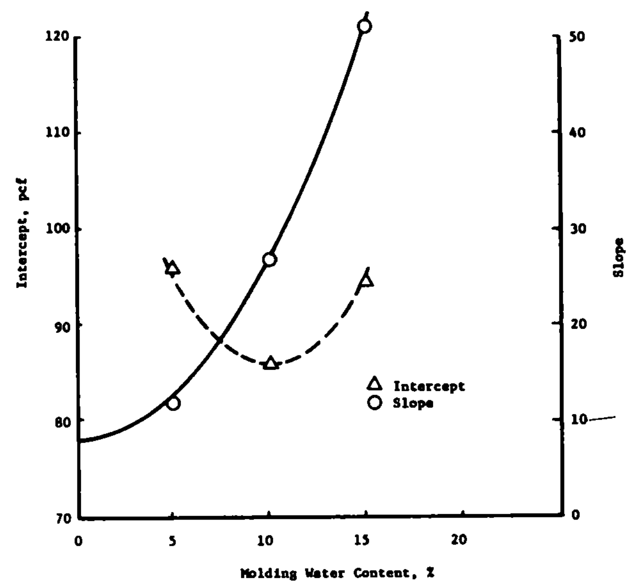


Figure 22 Intercept and slope (Eq. 9) versus molding water content for sandy topsoil.

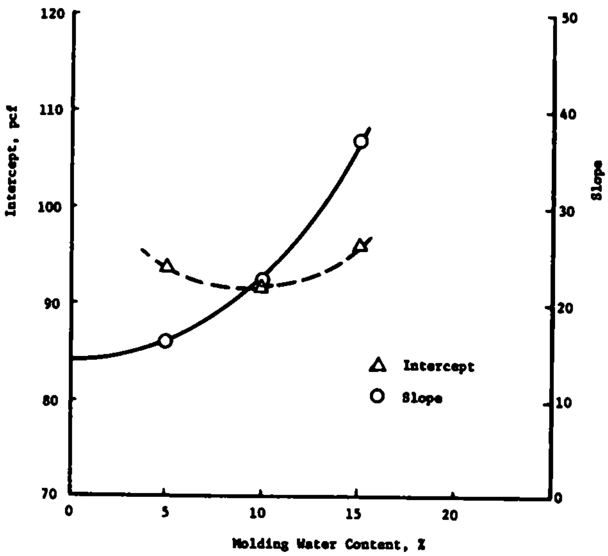


Figure 23 Intercept and slope (Eq. 9) versus molding water content for sand-clay mixture.

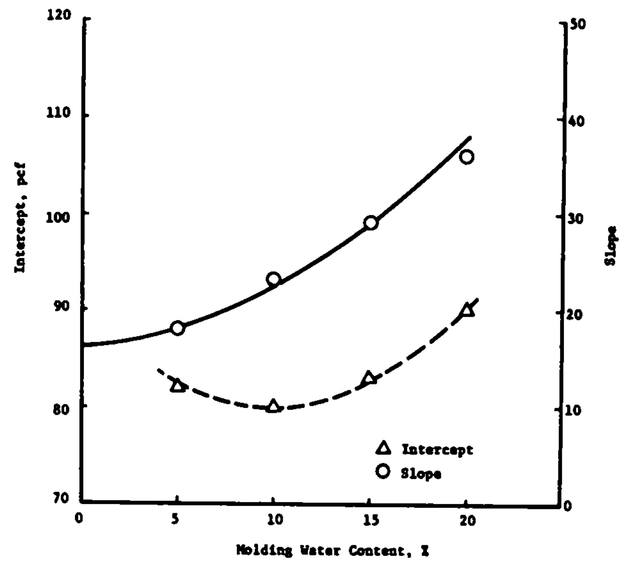


Figure 24. Intercept and slope (Eq. 9) versus molding water content for micaceous silty sand.

one at low to moderate density, and one at high density, and repeating these for a total of three different moisture levels. This calibration would be similar in nature to the conventional Proctor-type test presently used in construction control. With the proper size of mold, calibration of penetration resistance could be performed in conjunction with the Proctor-type test as part of the construction control procedure. To properly evaluate the penetration resistance at the moisture levels of greatest field significance, the moisture content at calibration should be about 50 percent of optimum for the lower level, about 80 percent of optimum for the intermediate level, and about 110 percent of optimum for the higher level. The six points thus obtained from the three moisture levels at two different compaction efforts should be plotted and calibration lines drawn on the semi-log plot as shown by Figure 14. The slope and intercept values of the three calibration lines should then be plotted on another graph as shown in Figure 20. The drawing of smooth curves to fit these slope and intercept points completes the calibration of the soil, and this graph in conjunction with Eq. 9 could be used to determine the density of soil at any site where the penetrometer test is performed in the field.

So that field density can be determined with the greatest speed and a minimum of calculations, the preparation of a master calibration chart, shown in Figure 25, is recommended. This chart was developed from Figure 20 for the red sand-clay material of this investigation using values of slope and intercept at 1 percent moisture increments within the useful range. Thus, the dry density of this material at a test site can be obtained from Figure 25 by laying a vertical straight edge on the penetration resistance scale to intersect the interpolated calibration line for the particular moisture content and reading the value of dry density opposite this intersection on the density scale. For example, if the soil compacted at optimum moisture (12.4 percent) has a penetration resistance of 4.1 blows/in., as indicated in Figure 25, a dry density of 110.2 pcf, or 95 percent compaction, has been obtained. In a similar manner, 5.9 blows per inch indicates a dry density of 116.0 pcf, or 100 percent compaction.

In the conventional in-situ density test using the water-balloon or sand-cone equipment, the moisture content of the soil must be determined to find the dry density of the soil. Likewise, the moisture content must be known to determine the dry density from penetration resistance. The net advantage in the use of the penetrometer would appear to lie in the fact that the penetration test can be performed in a few minutes and requires no surface preparation. Allowing about 10 minutes for the moisture content determination (using the Speedy moisture device), the total time required for the density determination using the penetrometer would be about 15 min for one man working alone. The total time required for the water-balloon or sand-cone test, including the moisture content measurement, is about 30 min to 1 hr, depending on the equipment used and the conditions encountered It is then a question of whether the time saved in using the penetration test procedure is enough to offset the added work required to develop the calibration chart for the particular material being tested. If the material is uniform and requires only one calibration chart for a large amount of road construction, such as would be the case with the base and subbase materials tested in this investigation, the benefits of the penetration test method are obvious. On the other hand, natural subgrade soils which vary from station to station might require too much calibration time to result in any net benefits. Even so, once the soil is calibrated the number of penetrometer tests that could be performed in that soil would not be as limited, and better test coverage of the roadway section could be accomplished. Also, another property of natural soils should not be ignored. The sensi-

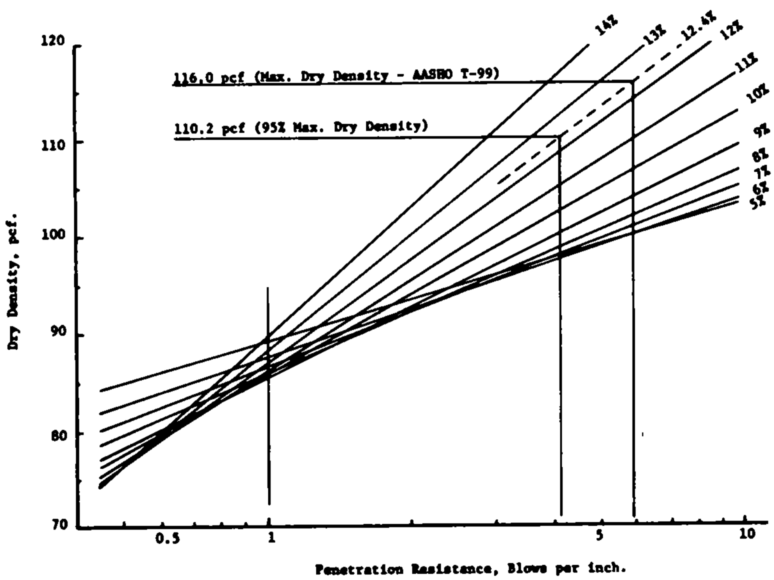


Figure 25 Calibration chart dry density versus penetration resistance for red sand-clay

tivity of natural soils to changes in moisture content, particularly when wetter than optimum, is greater than for granular materials. Therefore, in these cases, the moisture content of wet natural soils needs to be known with greater precision when determining the density from the penetration resistance.

The thixotropic behavior of some soil might result in changes in the penetration resistance versus density relationship established from calibration tests Therefore, it is recommended that field tests with the penetrometer be conducted as soon as possible after compaction of the fill material It is not expected that 1 or 2 hr of delay should be serious, but, until more data on this variable are obtained, the influence of longer waiting periods is questionable However, the obvious objective of any "rapid" construction control testing program is to proceed without delay, and, inasmuch as the penetration test can be performed quickly and is unaffected by the vibration of nearby equipment, there should be no trouble in following closely behind the earthwork operations. Thus, the question of the thixotropic behavior of roadway materials is more academic than practical

If the nuclear density-moisture gauge is used as the primary instrument to make limited construction control density measurements and also, at the same time, used to calibrate drop-hammer penetrometers, the number of useful total readings that could be made in a day with the combination of the two instruments would be significantly increased.

In summary, results have indicated that the drop-hammer penetrometer can be used effectively as a rapid means of estimating the dry density of several soil and base course materials. It is anticipated that the use of the penetrometer in the field would be restricted to those soils for which correlation can be established and, in addition, it is recommended that the time lag between compaction and penetrometer readings be kept to a minimum to reduce errors due to strengthening effects caused by drying

Density Measurements by Ultrasonic Transmission

The control of compaction by methods employing attenuation or transmission of vibrations through soil was determined to be theoretically feasible on the basis of a review of literature.

High-frequency oscillations have been used to evaluate material properties of elastic as well as viscoelastic materials Several references (*197-202*) indicate that the energy of waves propagated by oscillations can be related to the amplitude of the oscillation as well as to the distance from the wave source Ferry (*200*) and Barkan (*197*) present expressions for energy attenuation and wave propagation in various media which show the functional dependence of attenuation and propagation on the mass of the medium transmitting the oscillations. Waves passing through soil can be measured and recorded with the proper instruments placed on or below the surface. The development of the ultrasonic equipment used in this project was motivated by these principles.

Experiments using ultrasonic equipment were performed to determine the feasibility of this technique in determining the density of soils. Several different soil samples were compacted at several densities and moisture contents in 1-cu-ft molds and tested for transmission of upper sonic and ultrasonic vibration frequencies.

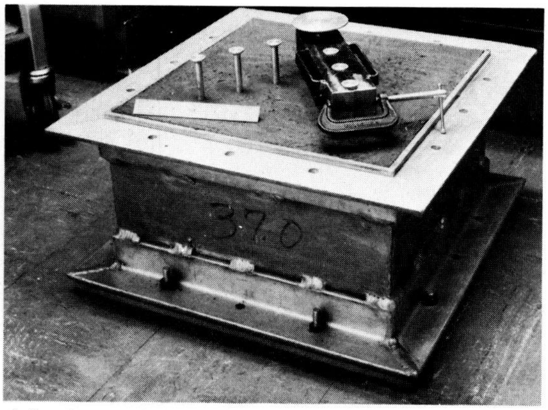
Operation of Equipment

The vibratory energy was transmitted to the soil through an aluminum peg driven into the soil near the center of the sample surface and the transmitted vibrations were picked up from six smaller but similar aluminum pegs that also were driven into the soil. The smaller pickup pegs were placed in two diverging rows and were located 2½, 4½, and 6½ in. from the driver peg, as shown in Figure 26a. Figure 26b shows all of the necessary ultrasonic equipment and appurtenances under actual test conditions. A block diagram of the test setup is shown in Figure 27.

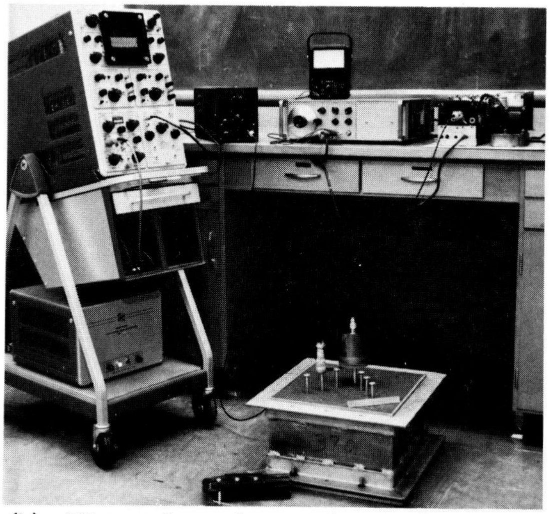
The function generator (oscillator) was set to furnish a constant 2.0-volt signal to the power amplifier that amplified the signal to provide a 60-volt driving signal to the 3-in.-diameter ceramic crystal drive unit (supplied on special order from Automation Industries, Inc., Boulder, Col.). The output surface of the drive unit was coupled to the machined top surface of the drive peg with a grease film. Although both the power amplifier and drive unit were capable of handling at least 25 watts of continuous driving power, a lower power level (approximately 2 watts) supplied by the amplifier was enough to induce necessary excitation to the sample under test. The ¾-in. ceramic crystal search unit (pickup transducer; also supplied from Automation Industries) was coupled to one of the smaller pegs with a grease film to sense the induced vibration of the sample, and this signal was fed to the tuned pre-amplifier and fed to a calibrated oscilloscope so that the peak-to-peak signal voltage could be identified and measured.

With the pickup unit directly coupled to the drive unit, the relative output of the over-all system was measured over the useful frequency range of the equipment. Figure 28 shows the resulting response curve. From the response curve, three test frequencies (12, 24, and 32 kc) were chosen to use natural output peaks in the lower, middle, and upper frequency ranges.

To explore the distribution of induced vibration throughout the sample, output voltage measurements were made on all six small pegs when the sample was driven at each of the three test frequencies. The nearest pegs (2½ in. from the driver) gave usable signals on all but a few dry, poorly compacted samples. Significant signals were also received from the center pegs, but they were more erratic and not as well correlated with density as were the stronger signals from the nearest pegs. Signals from the outer pegs (6½ in. from the driver) were generally too weak to provide any useful information and were often masked by stray pickup from the shielded cables coupling the various units of the system. Shielding was very important and it was necessary to completely shield the pickup transducer with aluminum foil to prevent the electric field associated with the drive unit from overpowering the desired vibration-induced signals from any of the small pegs. To prevent the pickup transducer from responding to unwanted acoustic signals transmitted through the air the drive unit was wrapped in a sound-absorbing flannel cloth.



(a) Compacted soil in form with aluminum pickup and driver pegs in position. The gage block shown is used to control peg spacing and depth.



(b) Ultrasonic equipment showing (left to right) oscilloscope, preamplifier, function generator and power amplifier. Driver and pickup transducers are positioned for testing.

Figure 26. Ultrasonic equipment and appurtenances.

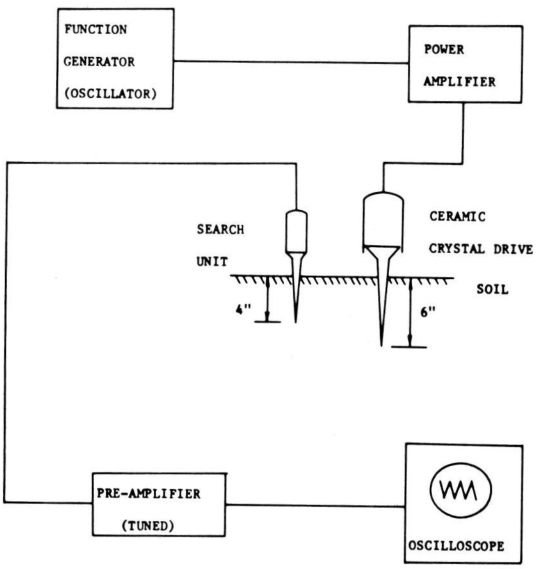


Figure 27. Ultrasonic equipment used for determining unit weight.

Test Results

Both sandy and fine-grained soils were prepared at various moisture contents and densities and tested by the ultrasonic method. Seventeen tests, summarized in Table 17, were performed on two sandy soils from the Coastal Plain Province of South Carolina A red clay soil and a mica silt soil representative of fine-grained soils from the Piedmont Province were tested in the same manner; the results of the 35 tests performed on these soils are given in Table 18.

Figures 29, 30, and 31 show a semi-log plot of dry density versus output voltage at the three test frequencies for sandy soils; Figures 32, 33, and 34 show the same plot for the fine-grained soils.

Results for the sandy soils were too scattered to evaluate the influence of moisture content on this series of tests. However, the fine-grained soils that were wet enough to exhibit some cohesion did not show great sensitivity to variations in moisture content. But the eight unusually dry fine-grained samples containing up to 12 percent moisture content tended to exhibit lower transmission than did samples with the same dry density compacted at higher moisture contents. These eight dry samples were plotted on the graphs (open symbols) but were omitted from regression analysis calculations.

Linear regression analysis was performed on each of the plots shown in Figures 29 through 34. The form of the regression equation is as follows.

$$\gamma = a + b \log E_f \qquad (12)$$

in which

γ = dry density, in pcf; and
E_f = output volts at frequency f(kc).

Table 19 gives the results of the regression analysis and lists the coefficients for the regression equation for each plot.

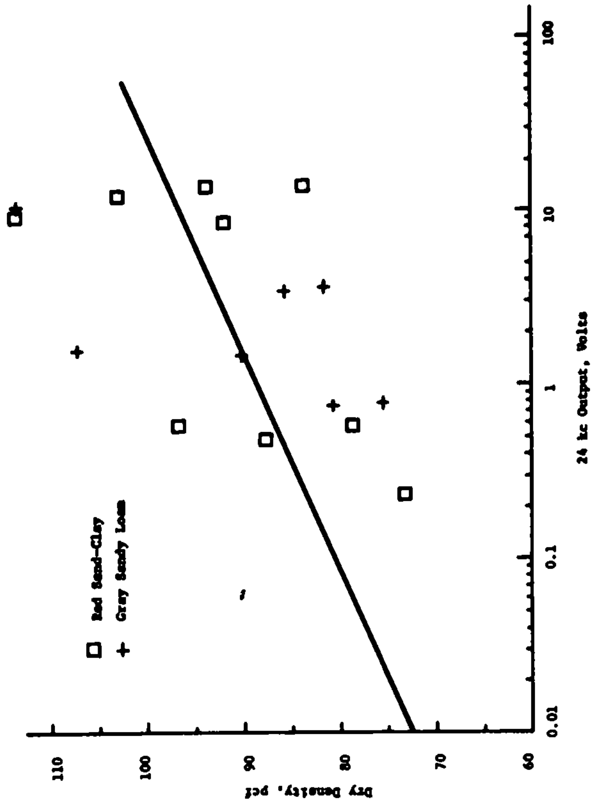


Figure 30. Dry density versus 24-kc output for sandy soils.

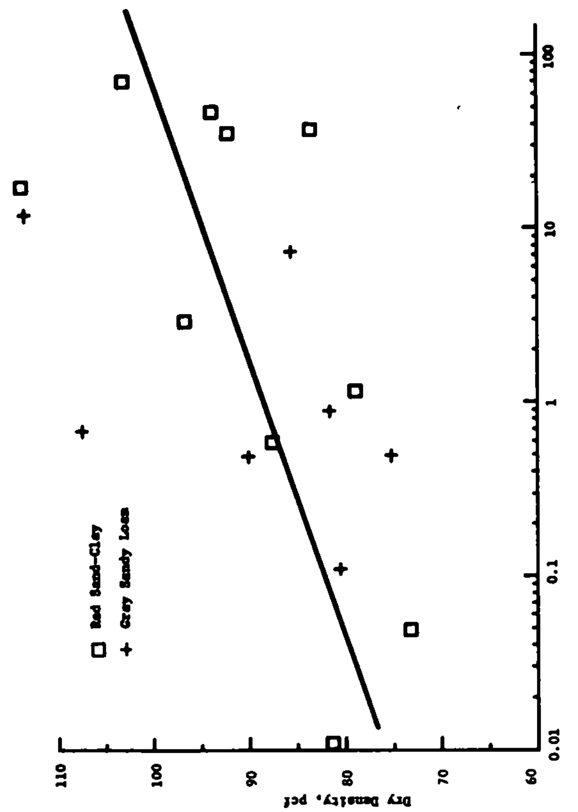


Figure 29. Dry density versus 12-kc output for sandy soils.

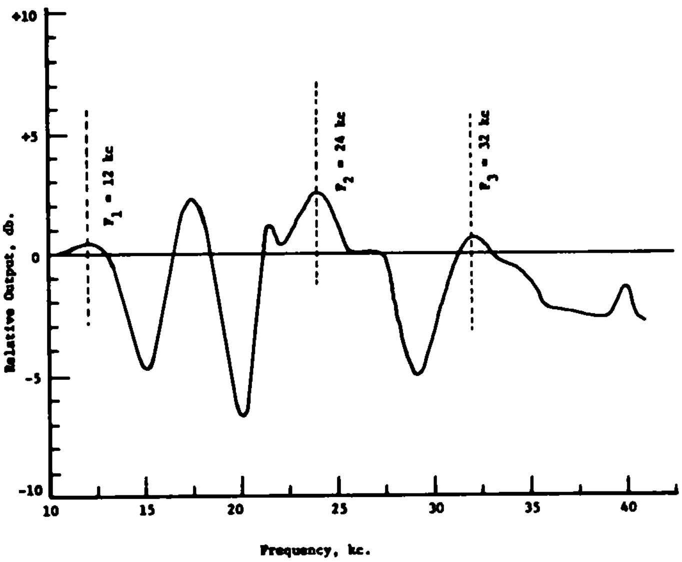


Figure 28 Over-all ultrasonic system response

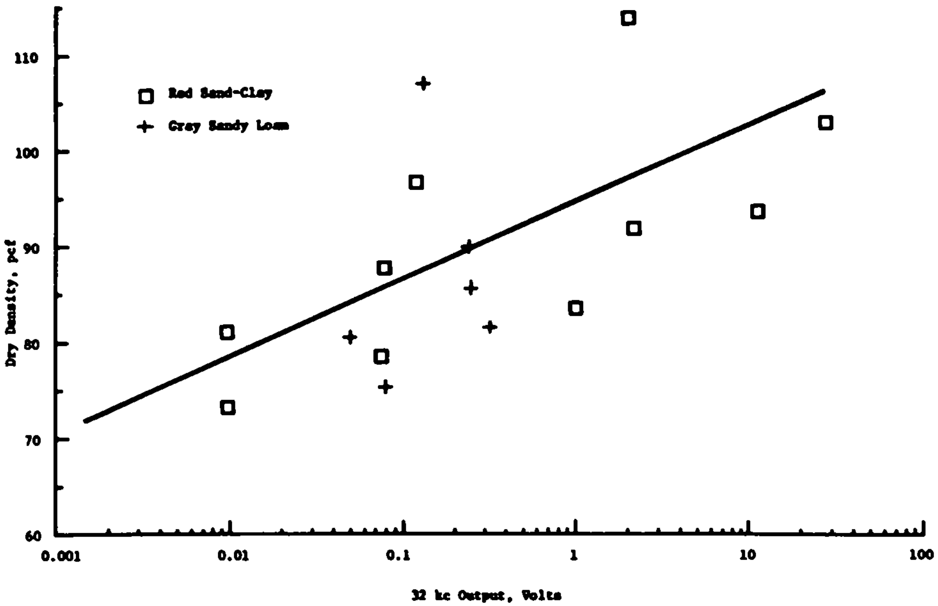


Figure 31 Dry density versus 32-kc output for sandy soils.

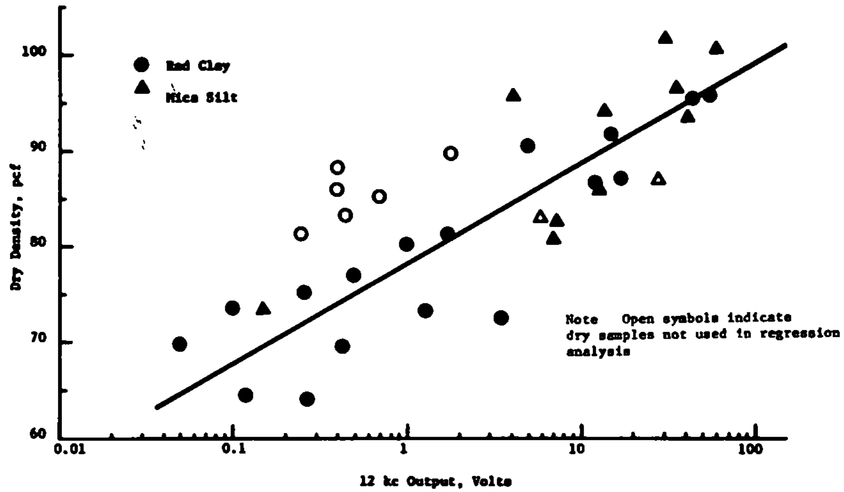


Figure 32 Dry density versus 12-kc output for fine-grained soils.

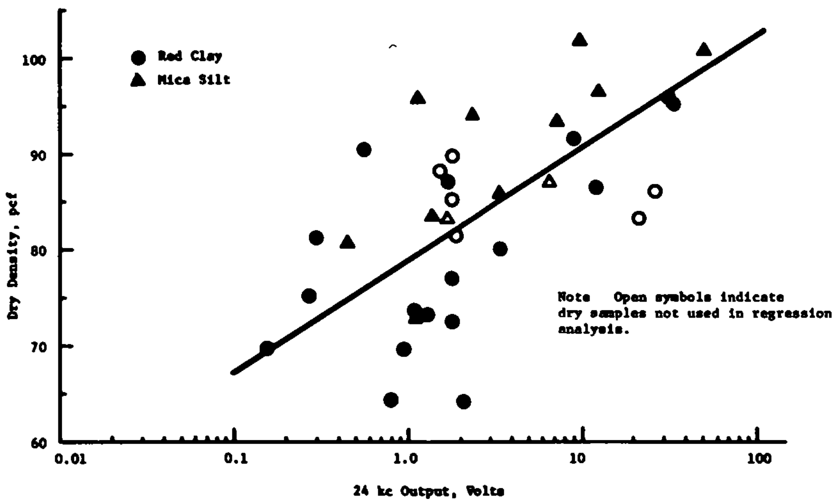


Figure 33. Dry density versus 24-kc output for fine-grained soils

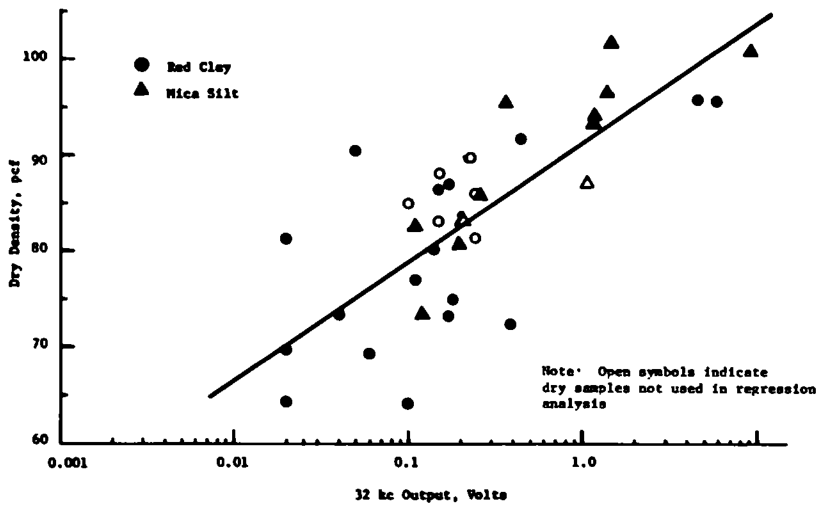


Figure 34. Dry density versus 32-kc output for fine-grained soils.

TABLE 17

SUMMARY OF ULTRASONIC TESTS ON TWO SANDY SOILS

SOIL TYPE	MOISTURE CONTENT (%)	DRY DENSITY (PCF)	VOLTS OUTPUT 2½ IN. FROM DRIVER AT: 12 KC	24 KC	32 KC
Red sand-clay	5 2	81 3	0 01	0.01	0 01
	5 2	87.5	0 60	0.60	0 08
	5 2	96 5	3 05	0 70	0 12
	9 3	73.1	0 05	0 24	0 01
	9 6	83 5	39 00	14.50	1.05
	9 4	93.6	49 00	14.70	11 50
	10.5	102.8	74 00	12 50	29.00
	14 5	78 5	1 20	0.60	0 04
	14 5	91 8	37 00	8.80	2 40
	14.0	113 6	18 00	9.50	2 10
Grey sandy-loam	10 1	75.3	0.50	0 80	0 08
	12.6	80 5	0 11	0 78	0 05
	13 9	85 6	7.60	3 50	0 25
	13 9	113 2	12 20	10.70	2 20
	19.3	81.6	0 90	3 70	0 32
	21 4	90 0	0 50	1.50	0 24
	18.0	107 2	0.70	1.60	0 13

TABLE 18

SUMMARY OF ULTRASONIC TESTS ON TWO FINE-GRAINED SOILS

SOIL TYPE	MOISTURE CONTENT (%)	DRY DENSITY (PCF)	VOLTS OUTPUT 2½ IN FROM DRIVER AT: 12 KC	24 KC	32 KC
Red clay	10 9	81.4[a]	0 25	1.90	0 24
	10 6	83 2[a]	0 45	2.20	0 15
	10 4	85 1[a]	0 70	1 80	0.10
	11 1	86 0[a]	0 40	2.70	0.24
	10 4	88.2[a]	0 40	1 55	0 15
	12 0	89 8[a]	1.80	1 80	0 23
	15 6	73 5	0.10	1.10	0 04
	15 1	75.2	0 26	0 27	0 18
	15.6	77 0	0 50	1.80	0 11
	16 1	80.1	1 00	3.50	0 14
	15.7	86 5	12.20	12.80	0 15
	14.5	87.0	17 50	1.70	0.17
	22 5	64 2	0.27	2.15	0 10
	22.9	64.4	0 12	0 80	0 02
	22 8	69 5	0 43	0.95	0.06
	22 1	73 3	1 30	1 30	0.17
	22 6	95 5	45.00	35.00	5 95
	22 8	95 7	56 00	33.00	4.60
	24 9	72 5	3.50	1.80	0 39
	25 1	91 7	15.00	9 50	0 45
	28 9	69.8	0.05	0.16	0 02
	29 9	81 3	1 70	0 30	0.02
	29 1	90 5	4.95	0 57	0 05
Mica silt	11.2	83.2[a]	6 10	1 75	0.21
	11 5	87 0[a]	28 50	5.90	1 10
	14 7	73 3	0.15	1 11	0.12
	14.3	86 0	13 00	3.60	0 25
	14.5	93 4	42 00	7.50	1 20
	15 0	100 8	61.00	52 00	9 50
	20.8	82 5	7.50	1.40	0 11
	20.7	96 5	36 00	13.00	1 40
	20.9	101 7	31 00	10 20	1 50
	26.3	80 8	7.00	0.46	0 20
	25 2	94.0	14 00	2.40	1 20
	26 0	95.7	4.20	1 15	0.37

[a] Omitted from regression analysis

Discussion of Ultrasonic Test Results

Although the statistical analysis revealed a definite correlation between density and output volts at all three test frequencies with all soils tested, the standard error obtained does not indicate, at present, a strong possibility of making accurate measurements of density by the application of ultrasonics. Coupling of the driver and pickup transducers to the soil is a problem that was not completely solved. The use of aluminum pegs driven into the soil was the most repeatable method devised, but variations as high as three to one within the same sample were often encountered when comparing the output reading from one pickup peg with another similarly placed peg. Replicate measurements would reduce some of this experimental error, but the standard error of about 10 pcf for the sandy soils is too high to reduce the error to an acceptable level with a reasonable number of replications

The outlook for fine-grained soils using the 12-kc test frequency is more promising, although the 5.2-pcf standard error obtained with these soils is still too high to satisfy the requirements of construction control testing. However, possible refinements in the technique or choice of a lower test frequency within the sonic range might bring the precision within acceptable limits. The use of a sonic test frequency, which includes the 12 kc found to be most successful in the investigation, would permit the use of simpler, lower cost, low-impedance, magnetic-type transducers that could be directly coupled to the pickup pegs. Direct coupling also would eliminate the moderate variations noted in the grease film coupling used in the investigation. Redesign of the soil coupling pegs also might result in more efficient coupling of the transducers to the soil in order to minimize the error due to variations in driver and pickup coupling. By the use of transistorized amplifiers, relatively simple, lightweight, battery-operated equipment could be developed to provide the modest power requirement needed to run the driver transducer and meter circuits.

The mechanism of energy transfer through the soil appears to be related to the cohesion of the soil at compaction moisture content and this could account for the more erratic results obtained for the sandy soils. The relatively low transmission of the dry samples is evidence that supports this theory Abnormally wet samples also indicated somewhat poorer transmission characteristics, although the effect was not as noticeable as for the very dry samples The discrimination against soils of abnormally low or high moisture content is no great problem in applying the technique to the control of earthwork, inasmuch as proper compaction of soils outside the optimum moisture range is, at best, difficult. Thus, if the ultrasonic (or sonic) testing device is calibrated with soils compacted at normal (near optimum) moisture content, the use of this technique would also have built-in controls against construction compaction at improper moisture content.

The very short time (estimated at no more than a few minutes) to perform the test is strong reason for continued development of an ultrasonic (or sonic) transmission testing device. However, present indications are that the application of this method of testing might be limited to fine-grained soils only. Future developments and improvements might widen the possibilities to include sandy soils, but it is doubtful if the technique would ever find useful application to crushed stone or other granular materials containing large particles.

TABLE 19

REGRESSION ANALYSIS COEFFICIENTS FOR ULTRASONIC TESTS ON SANDY AND FINED GRAINED SOILS

SOIL TYPE	TEST FREQUENCY (KC)	REGRESSION EQ COEFFICIENTS a	b	COEF OF CORR	STANDARD ERROR (PCF)
Sandy	12	88.4	6.2	0.55	10.6
	24	88 3	8.0	0.52	10.8
	32	94 5	8.0	0.63	9.8
Fine-grained	12	78.2	10 4	0.89	5.2
	24	79.0	11.5	0.67	8.3
	32	91.4	12.0	0.74	7.6

CHAPTER FOUR

CONCLUSIONS AND APPLICATIONS

CONCLUSIONS

The study of rapid test methods for field control of highway construction brought forward a number of conclusions which are summarized in the following paragraphs

Time Limits for Rapid Tests

Materials specifications have long reflected the necessity of requiring a minimum number of tests for determining the quality of material or work to be accepted. Usually the number of such tests was chosen arbitrarily. In some cases the number of tests was based on how much time and money were available for these tests. Selection of samples was frequently conducted by dividing these tests among what the inspector considered good, average, and poor material. If statistics are to be applied correctly, then sample selection must be free of such bias; otherwise, efforts to project the attributes of the samples to the entire quantity of material will be thwarted.

The number of tests required for a meaningful statistical analysis will be influenced by the quantity of material to be accepted (lot size), the degree of confidence that the samples are truly representative of the lot, the sample size, and the variabilities of material and test method. Determination of lot size is not entirely a statistical problem, but one of economics. From the statistical point of view, the lot should be fairly homogeneous so that a reasonable number of samples can accurately predict its properties The economic factors are two-fold: first, the contractor desires to know as soon as possible whether the work he has completed is acceptable; and second, in the event the material is unacceptable, the lot size should be small enough so that the replacement or modification cost is not a deterrent to its rejection.

To keep delays of construction to a minimum, the lot is further influenced by production rate, test time, and the decision time for analysis of test data. In addition, samples should be taken only after the lot has been completely produced; otherwise, the normal distribution of test results which is generally assumed is less probable. The total test time will depend on the sampling plan selected for the given material, which in turn must be selected according to the level of confidence acceptable. After the number of tests required for accurate evaluation of acceptability of a given material or process has been determined, the maximum time for acceptance testing to keep pace with construction may be calculated. This calculation is made considering the lot production time, the decision time, and the number of tests required

Current Practice

Analysis of data obtained from questionnaires and personal interviews indicates that the majority of state highway departments still make general use of standard or slightly modified AASHO and ASTM test procedures for field control of construction. Actual use is approximately 75 percent for AASHO and ASTM procedures, while about 25 percent of the testing consists of the use of special test procedures Answers to questionnaires also indicated that about 80 percent of the special test procedures used by the various states are considered to be rapid, whereas only 17 percent of the AASHO and ASTM procedures are classed as rapid test methods.

Priority of Need for Rapid Tests

Areas of highway construction with the greatest need for rapid tests were determined from personal interviews with state highway department personnel, questionnaires completed by highway departments and contractors, as well as an extensive literature survey. A review of time limits for rapid testing indicated criteria that could be used in evaluating testing speed and accuracy by use of statistics. The areas of greatest need for more rapid test methods included compaction control as well as asphalt content determination and base course gradation.

Asphalt Content

The ignition method provides an inexpensive, rapid procedure for estimating the asphalt content of paving mixtures. The calculated asphalt content can be estimated within ±¼ percent of the actual asphalt content of the mix. Successful application of the method is contingent on negligible weight loss of the aggregates or prior calibration to account for this loss.

Asphaltic Concrete Compaction

Removal of representative hot-mix pavement specimens by the use of a cup formed from a thermoplastic material was found to be both simple and inexpensive. It is estimated that a specimen can be made available for density determination within 20 min if that portion of the pavement containing the cup is subjected to accelerated cooling by use of dry ice. One possible deterrent to the adoption of sampling by use of the thermoplastic cup is the fact that positioning the plastic cup has the effect of predetermining the sampling location. Hence, inspection will be necessary to ensure that nonuniform rolling techniques are not introduced.

Gap Sieving

The use of a single sieve for estimating gradation specification conformance of base course materials is justified when the proximity of initial gradation to specification limits and degradation characteristics of the particular base material are considered. Samples of three base course materials conforming to the same gradation with a nominal maximum size of 2 in. were subjected to mechanical degradation in the laboratory. The greatest changes in gradation occurred consistently on the ½-in. and 1-in. sieves.

Compaction Control—Penetrometer

Laboratory data support the use of a penetrometer for rapidly estimating the unit weight of base and compacted soils with relatively good accuracy. No surface preparation of the soil is necessary and field measurements can be made in approximately 5 min; however, moisture content needs to be known.

Ultrasonic Transmission

In another part of this study it was found that vibrations in the 10-kc to 50-kc range, generated and detected by ceramic crystal transducers, could be transmitted through several inches of soil. When the transducers were coupled to the soil by means of aluminum pegs, the transmitted signal was directly related to the density of the soil. The transmission appeared to be relatively independent of moisture contents used in soil compaction in this study.

Potential Uses of Electromagnetic Radiation

The use of devices employing electromagnetic radiation for the determination of bulk and composite properties of soil, aggregate, and cementing materials did not appear to be feasible at the time of this study. The main obstacle restricting extensive use of regions of the spectrum other than X-rays or gamma rays appears to be the fact that phenomena arising in other regions are surface effects and cannot give reliable information about the interior.

APPLICATIONS

Several recommendations regarding rapid construction control test methods and equipment are summarized in this section. Recommendations concerning application of the findings of the study are made on the basis of results obtained in field and laboratory testing carried out during this investigation.

1. The ignition method for determining rapidly the asphalt content of paving mixtures is recommended for field use where aggregate weight loss at relatively high temperatures does not preclude accurate estimation of asphalt content.
2. The use of a thermoplastic cup, similar to the one developed in this study to assist in removal of samples of hot-mix paving mixtures, is recommended when unit weight determinations based on fluid displacement techniques are used.
3. Use of a single sieve for estimating compliance with gradation specifications is suggested when the gradation of the material delivered to the job site is controlled at the source of supply.
4. A drop-hammer penetrometer can be used to determine rapidly the unit weight of compacted soil material or base material when the moisture content is known and prior calibration with the particular material has been established.
5. Further development and evaluation studies are recommended to determine possible utility of the ultrasonic transmission device developed in this study for measuring the unit weight of compacted soil.

REFERENCES

1. McMahon, T. F., "Research and Development in Application of Quality Control to Highway Construction." *Proc. 50th Annual Road School,* Purdue Univ, pp. 39-43 (Mar 1964).
2. Izatt, J. O., "Introduction." *STP No. 362,* ASTM, p. 1 (June 1963).
3. "ASCE Initiates Information Retrieval Program." *Civil Eng.*, Vol. 33, pp. 28-29 (Jan 1963).
4. AASHO, *Standard Specifications for Highway Materials and Methods of Sampling and Testing. Part II. Methods of Sampling and Testing* 8th ed. (1961).
5. Wood, J. E., "A Method of Extracting Asphalt from Large Samples of Asphalt Concrete." *Proc. Assn of Asphalt Paving Technologists,* Vol. 18, pp. 138-153 (1949).
6. *Lee, A. R., Gough, C. M., and Green, E. H., "A Rapid Method of Analysis for Bituminous Material." *Roads and Road Const.* (London), Vol. 29, No. 341, pp. 128-130 (May 1951).
7. *Taylor, F. G., and Tattersall, E., "The Road Research Laboratory Machine for Rapid Analysis of Bituminous Road Materials." *Roads and Road Const.* (London), pp. 131-132 (May 1951).
8. *Brakley, B. A., "A Vacuum Extractor for Bituminous Mixtures." A paper presented at ASTM 68th Ann. Meeting, Lafayette, Ind. (June 1965).
9. *Holland, L. E., "Asphalt Content of Bituminous Mixtures." A paper presented at ASTM 67th Ann. Meeting, Chicago (June 1964).
10. Rice, J. M., "Volumeter Methods for Measuring Asphalt Content and Effective Gravity of Aggregates in Bituminous Mixtures." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 22, pp. 284-301 (1953).
11. *Lamb, D. R., and Zoller, J. H., "Determination of Asphalt Content of Bituminous Mixtures by Means of Radioactive Isotopes." *Proc. HRB,* Vol. 35 (1956) pp. 322-326.
12. *Walters, H. W., "Nuclear Asphalt Content Determinations at the Job Site." *Hwy. Res. Record No. 117* (1966) pp. 54-70.
13. Howard, P. K, and Covault, D. O., "The Use of Nuclear Methods to Measure and Mineral Filler Content and Asphaltic Content of Bituminous Concrete." (An abridgement) *Hwy. Res. Record No. 66* (1965) pp. 84, 85.
14. Varma, M. M, and Reid, G. W., "Determination of Asphalt Contents in an Asphaltic Pavement by Thermal Neutrons." (An abridgement) *Hwy. Res. Record No. 66* (1965) pp. 73-83.
15. *Hughes, C. S., "Density and Asphaltic Content of Bituminous Pavements," A report given for HRB Special Committee No. 8 (Sept. 28-29, 1964).
16. *Richardson, C., *The Modern Asphalt Pavement* 2nd ed., Wiley, pp. 351, 514 (1908).

* Abstract appears in Appendix E

17. *SMITH, W. F., "The Supplementing of Laboratory Control of Hot Mix Plants by Simple Manual Tests." *Proc. Assn. of Asphalt Paving Technologists*, Vol 24, pp. 392-398 (1955).
18. STEVENS, D. E, "Fundamentals of Stability Testing of Asphaltic Mixes" *Proc. Assn of Asphalt Paving Technologists*, Vol. 22, pp. 364-382 (1953)
19. THE ASPHALT INSTITUTE, *Mix Design Methods for Hot-Mix Asphalt Paving* 1st ed. (1956).
20. *CHU, T. Y, and SPANGLER, M. G, "Plant Stability Test for Hot-Mix Asphaltic Concrete Mixtures." *Roads and Streets*, pp 83-92 (Oct. 1950).
21 WILLIAM, F M., GRIMMER, L. E MCADAMS, M. M, and YANOSHEK, S Y, "Measurement of Bituminous Concrete Core Specific Gravities and Specific Gravities of Bituminous Coated Coarse Aggregate by Means of a Volumeter" *STP No. 191*, ASTM, pp. 4-24 (1956).
22. KIMBLE, F. W., "A Field Method of In-Place Density Determination and Control of Hot Mix Asphaltic Concrete." *Proc. Assn. of Asphalt Paving Technologists*, Vol. 27, pp. 265-293 (1958)
23. *SLOANE, R L, "Development of a Nuclear Surface Density Gage for Asphaltic Pavements." *HRB Bull 360* (1962) pp 1-17.
24. *HUGHES, C. S., "Investigation of a Nuclear Device for Determining the Density of Bituminous Concrete." *Proc Assn. of Asphalt Paving Technologists*, Vol. 31, pp. 400-417 (1962).
25. *HUGHES, C S., and RALSTON, H. H., "Field Testing of a Nuclear Density Device on Bituminous Concrete." *Proc Assn. of Asphalt Paving Technologists*, Vol. 32, pp. 106-147 (1963).
26. RICE, J. M., "The Measurement of Voids in Bituminous Mixtures by Pressure Methods." *Proc Assn of Asphalt Paving Technologists*, Vol. 21, pp. 92-119 (1952).
27. LARSEN, O. "Development and Use of High Pressure Apparatus for Determining Voids in Compacted Bituminous Concrete Mixtures" *Proc Assn. of Asphalt Paving Technologists*, Vol. 26, pp. 403-436 (1957).
28. *EKSE, M., and ZIA, Z T, "Field Measurement of Air-Permeability for Control of Bituminous Mat Construction." *Proc Assn of Asphalt Paving Technologists*, Vol. 22, pp. 44-55 (1953)
29. *ELLIS, W. H, and SCHMIDT, R. J., "A Method for Measuring the Air Permeabilities of Asphalt Concrete Pavements." *STP No. 294*, ASTM, pp. 85-91 (1960).
30. *HEIN, T. C., and SCHMIDT, R. J., "Air Permeability of Asphalt Concrete." *STP No 309*, ASTM, pp. 49-62 (1961).
31. *KARI, W. J., and SANTUCCI, L E, "Control of Asphalt Concrete Construction by the Air Permeability Tests" *Proc. Assn of Asphalt Paving Technologists*, Vol. 32, pp. 148-170 (1963).
32. WARNER, D. B, and MOAVENZADEH, F., "Permeability-Compaction Characteristics of Bituminous Mixtures" A paper presented at ASTM 67th Ann. Meeting, Chicago (June 1964).
33. *SOILTEST, INC., *Operations Manual. Asphalt Paving Meter.* (1963)
34. *PYK, N. C, HATHAWAY, C. W, and WARNICK, C. C., "Development of an Asphalt Pavement Air Permeater and Evaluation of Its Use." *Res. Report 2*, Eng Experiment Station, Univ of Idaho (Sept. 1965).
35 *ZUBE, E., "Permeability Test." *Calif Highways and Pub. Works*, pp. 53-63 (July-Aug. 1963).
36. RICE, J. M, "New Test Method for Direct Measurement of Maximum Density of Bituminous Mixtures" *Crushed Stone J*, Vol 28, No 3, pp. 10-17 (Sept. 1953).
37. RICE, J. M., "Maximum Specific Gravity of Bituminous Mixtures by Vacuum Saturation Procedure." *STP No. 191*, ASTM, pp 43-55 (1956).
38. SERAFIN, P. J, "Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion" *Proc. Assn. of Asphalt Paving Technologists*, Vol. 23, pp. 480-501 (1954).
39. RICKETTS, W. C, SPRAGUE, J. C, TABB, D D., and MCRAE, J. L., "An Evaluation of the Specific Gravity of Aggregates for Use in Bituminous Mixtures" *Proc ASTM*, Vol. 54, pp 1246-1257 (1954)
40. MCRAE, J. L., "Specific Gravity and Voids Relationships in Bituminous Pavement Mix Design" *STP No. 191*, ASTM, pp. 62-68 (1956)
41 MARTIN, J. R, and LAYMAN, A H, "Development and Application of the Effective Specific Gravity of Bituminous Coated Aggregates" *STP No 191*, ASTM, pp. 38-42 (1956)
42. FOX, W. E, and Page-Hanify, D. S., "A Method of Determining Bulk Density of Soil" *Soil Science*, Vol. 88, No. 3, pp 168-171 (Sept 1959).
43. STEVENSON, W. H., "A New Soil Sampler." *Bull. No 94*, Iowa Agri Experiment Station, Iowa State Univ., pp. 31-34 (1908).
44. ISRAELSON, O. W., "Studies on Capacities of Soils for Irrigation Water and on a New Method for Determining Volume Weights." *J. Agricultural Research*, Vol. 13, pp. 1-35 (1918)
45 FREAR, W, and ERB, E. S, "Excavation Method for Determining the Specific Gravity of Soils" *J. Assn. of Official Agricultural Chemists*, Vol. 4, pp. 10-14 (1920).
46. BECKETT, S. H, "The Use of Highly Viscous Fluids in the Determination of Volume Weight of Soils." *Soil Science*, Vol. 25, pp. 481-483 (1928).
47. VEIHMEYER, F J., "An Improved Soil Sampling Tube" *Soil Science*, Vol. 27, pp. 147-151 (1929).
48 HUMPHRES, H. W., "Are You Getting Good Compaction?" *Western Construction*, pp. 84-86, 96 (June 1954)
49. HUMPHRES, H. W., "A Critical Look at Density Tests." *Western Construction*, pp. 54, 58, 69 (Nov. 1961).

50 National Limestone Institute, "Quality Control —Field Density." *Tech. Info. Release No. 14* (1964).
51. State of California, "Test Method No. Calif. 216-F." *Materials Manual. Testing and Control Procedures*, Vol. 1, Div. of Highways (1963).
52 *Minor, C E, and Humphres, H. W., "A New Method for Measuring In-Place Density of Soils and Granular Materials." *HRB Bull. 93* (1954) pp. 49-60
53. *Brand, L, "A Study of the Sand Cone and Rainhart Volumeter Methods of Measuring the Volume of Density Test Holes" *Research Report*, Va. Council of Highway Invest. and Research, Charlottesville (Nov. 1961).
54 *Coffman, B. S., "Controlling Accuracy with a More Rapid Sand Cone Density Test" *ASTM Bull. No. 218*, pp. 57-59 (Dec. 1956).
55. Miller-Warden Associates, "Effects of Different Methods of Stockpiling and Handling Aggregates." *NCHRP Report 46* (1964) pp. 1-102.
56. Gunn, R. W, "A Study of Degradation and Densification of an Aggregate Base Course Under Traffic." *Research Report*, Va. Council of Highway Invest and Research, Charlottesville (May 1963).
57. Chu, T Y., and Davidson, D. I., "Simplified Air-Jet Dispersion Apparatus for Mechanical Analysis of Soils." *Proc. HRB*, Vol 32 (1953) pp. 541-547.
58. Handy, R. L., and Davidson, D. T., "Pipette Method to Supplement Hydrometer Test for Particle-Size Determination in Soils." *Proc. HRB*, Vol. 32 (1953) pp 548-555.
59. Coulter, J. R., and Kinsman, S., "Particle Size Measurements Using the Resistance Change Principle." A paper presented at the 63rd Ann. Meeting, Amer. Ceramic Soc, Toronto (Apr. 1961).
60 *Hveem, F. N., "Sand-Equivalent Test for Control of Materials During Construction." *Proc. HRB*, Vol. 32 (1953) pp 238-250.
61. "Methods of Determining Maximum Dry Unit Weight and Optimum Moisture Content for Materials Containing Coarse Aggregate." *HRB Bulletin 319* (1962) pp 81-98.
62. *Mainfort, R. C, and Lawton, W. L., "Laboratory Compaction Test of Coarse-Graded Paving and Embankment Materials" *Proc. HRB*, Vol. 32 (1953) pp. 555-566.
63. U.S. Department of the Interior, "Compaction Test for Soil Containing Gravel." Designation E-38, *Earth Manual*, 1st ed., rev., Bur. of Reclamation, Denver (1963).
64. *Johnson, A. W., and Sallberg, J. R., "Principle Methods for Determining Maximum Unit Weight and Optimum Moisture Content." *HRB Bull. 319* (1962) pp. 4-20.
65. *Pettibone, H. C., and Hardin, J., "Research on Vibratory Maximum Density Test for Cohesionless Soils." A paper presented at ASTM Ann. Meeting, Denver (June 1964).
66. *Chamblin, B. B., Jr. "Compaction Characteristics of Some Base and Subbase Materials. *HRB Bull. 325* (1962) pp. 1-21.
67. *Humphres, H. W., "A Method for Controlling Compaction of Granular Materials." *HRB Bull 159* (1957) pp. 41-57.
68. Humphres, H. W, personal communication (Jan. 1965).
69 Zeigler, E. J., "Effect of Material Retained on the No. 4 Sieve on the Compaction Test of Soils." *Proc. HRB*, Vol 28 (1948) pp. 409-414.
70. U.S. Department of Commerce, *Standard Specifications for Construction of Airports* Office of Airports, CAA, p. 572 (Jan. 1948).
71. *Turner, C. H., "Chart Method Gives Unit Weight of Crushed Base Stone." *Roads and Streets*, pp. 62-63 (Dec. 1954)
72. James, H. D., and Larew, H. G., "Compaction of Coarse-Grained Granular Materials." *Proc. HRB*, Vol. 40 (1961) pp. 676-680.
73 Nichols, F. P., Jr, and James, H. D., "Suggested Compaction Standards for Crushed Aggregate Materials Based on Experimental Field Rolling." *HRB Bull. 325* (1962) pp. 22-43.
74. *Croney, D, and Jacobs, J. C., "The Rapid Measurement of Soil Moisture Content in the Field." *Roads and Road Const* (London), Vol. 29, No. 353, pp. 191-194 (July 1951).
75. *Ivanov, P. V., "A Rapid Method of Determining Soil Moisture" (In Russian), *Pochvovedenie* (Russia), Vol. 3, pp. 61-65 (1953).
76. *Houlnick, C, "Water Content of Sands." (In French), *Annales des Ponts et Chaussées* (Paris), Vol. 121, No. 6, pp. 176-177 (1951).
77. *Bloodworth, M. E, and Page, J. B., "Use of Thermistors for the Measurements of Soil Moisture and Temperature." *Proc. Soil Science Soc. of America*, Vol. 21, No 1, pp. 11-15 (Jan.-Feb. 1957).
78. *Perrier, E. R, and Evans, D. D., "Soil Moisture Evaluation by Tensiometers." *Proc. Soil Science Soc. of America*, Vol 25, No. 3, pp. 173-175 (May-June 1961).
79. *Kirkham, R. H. H., "A Buoyancy Meter for Rapidly Estimating the Moisture Content of Concrete Aggregates." *Civil Eng. and Pub. Works Review* (London), Vol. 50, No. 591, pp. 919-980 (Sept. 1955)
80. *McIntosh, J. D, "The Siphon-Can Test for Measuring the Moisture Content of Aggregates." *Res. Note Report 6*, Cement and Concrete Assn. (London) (1951).
81. Turnbull, J. M., "New Test for Control of Cohesive Soils in Rolled-Fill" *Proc. ASCE, J. of Soil Mechanics and Foundations Div.*, Vol. 82, No. SM2, pp. 1-11 (1956).
82. *U.S. Department of Commerce, *Hydraulic Proctor Needle*. Soils Branch, Div. of Phys. Research, BPR (May 1958).
83. *Blystone, J. R., Pelzner, A., and Steffens, G P., "Moisture Content Determination by the Calcium Carbide Gas Pressure Method." *Pub. Roads*, Vol. 31, No. 8, pp. 177-181 (June 1961).

84. *STEFFENS, G. P., and RING, G. W., "Advances in Methods for Field Testing of Densities and Moisture Content of Earthwork, Base, and Surface Courses." A paper presented at AASHO 46th Ann. Meeting, Detroit (Dec. 1960).
85. *THOMAS, W. F, "Moisture Determination in Soils and Stabilized Soils." *Roads and Road Const.* (London), Vol. 36, No 425, pp. 140-147 (May 1958).
86. *TEXAS A&M UNIVERSITY, "New Soil Moisture Tests" *Texas Eng Experiment Station News*, Vol. 1, No. 1 (Mar. 1950).
87. *VAN DER MAREL, H. W., "Rapid Determination of Soil Water by Dielectric Measurement of Dioxane Extract." *Soil Science*, Vol. 87, No. 2, pp. 105-119 (Feb 1959).
88. *HANCOCK, C. K., and HUDGINS, C. M., JR, "Determination of Water in Soils by an Indirect Conductivity Method." *Analytical Chemistry*, Vol. 26, No 11, pp. 1738-1740 (Nov. 1954).
89 *TEXAS A&M UNIVERSITY, "Indirect Conductivity Method Reveals Soil Moisture Content in Brief Time." *Texas Eng. Experiment Station News*, Vol. 8, No 1, pp. 15-16 (Mar. 1957).
90. *SANDOVER, J A., "Electrical Determination of the Moisture in Sand" *Proc. ASCE, J. of Construction Div*, Vol. 88, No. CO2, pp. 25-39 (Sept. 1962).
91. *JOHNSTON, W. R., and PERRIER, E. R, "Use of Direct and Alternating Current Meters for Measuring Resistance of Soil Moisture Units." *Soil Science*, Vol 91, No. 6, pp. 360-363 (June 1961).
92. *ROWLAND, E F., FAGAN, T D, and CRABB, G A., JR., "A Slide Rule for Soil Moisture Determination." *Agric Eng.*, Vol 35, No. 3, pp. 163-164 (Mar 1954).
93. *DE PLATER, C. V, "A Portable Capacitance-Type Soil Moisture Meter." *Soil Science*, Vol. 80, No. 5, pp 391-395 (Nov. 1955).
94. *BALLA, A., "Rapid Soil-Moisture Determination in the Field, Without Sampling." *Agrarudomany*, Vol. 3, pp 430-435 (1951).
95. *REDUS, J F., "A Study of In-Place Density Determination for Base Courses and Soils." *HRB Bull. 159* (1957) pp. 24-40.
96. GEORGIA STATE HIGHWAY DEPARTMENT, "Method for Determining Rapid Field Density of Soils" Test Method GHD-30, *Field Sampling, Testing and Inspection Manual* (1958).
97 STATE ROAD DEPARTMENT OF FLORIDA, "Evaluation of a Nuclear Density-Moisture Apparatus." *Research Bull No 55*, Div. of Research and In-Service Training (Feb. 1961)
98. PROCTOR, R. R, "Fundamental Principles of Soil Compaction." *Eng. News-Record*, Vol. 111, No. 9 (Aug. 31, 1933).
99. HVEEM, F. N., "Maximum Density and Optimum Moisture of Soils" *HRB Bull 159* (1957) pp 1-21.
100. U.S. DEPARTMENT OF THE INTERIOR, "Rapid Compaction Control." Designation E-25, *Earth Manual*, 1st ed., rev., Bur. of Reclamation, Denver (1963).
101. WOODS, K. B, and LITEHISER, R. R., "Soil Mechanics Applied to Highway Engineering in Ohio" *Bull. 99*, Eng Experiment Station, Ohio State Univ. (July 1938).
102. OREGON STATE HIGHWAY DEPARTMENT, "Procedure for Determination of 100 Percent Relative Maximum Density and Optimum Moisture of Soils." *Manual of Instructions for Sampling-Testing Procedures-Documentation of Construction Materials.*
103. RING, G. W., III, SALLBERG, J. R., and COLLINS, W. H., "Correlation of Compaction and Classification Test Data of Soils." *Pub Roads*, Vol. 32, No 4, pp. 77-87 (1962).
104. *"Air Content Test May Improve Soil Compaction Specifications." *Surveyor and Municipal and County Eng.*, Vol. 114, No. 3317, pp. 965-966 (1955).
105 ROSTRON, J. P., "Cracking and Performance of Asphaltic Wearing Surfaces of Certain Highway Sections." *Bull 100*, Eng. Experiment Station, Clemson Univ (June 30, 1963).
106. TURNBULL, W J., and FOSTER, C. R, "Proof-Rolling of Subgrades." *HRB Bull. 254* (1960) pp. 12-22.
107. SINGH, A., and RANJAN, C., "Some Investigations on California Bearing Ratio and North Dakota Cone Tests and Their Correlation." *Roads and Road Constr.* (London), Vol. 38, No 446, pp. 53-55 (1960).
108 HOUSEL, W. S, "Suggested Method of Test for Ultimate Shearing Resistance of Cohesive Clay Soils by the Penetration Method" *Procedures for Testing Soils*, ASTM (Apr. 1958).
109 *MURAYAMA, S., UESHITA, K., and SAITO, M., "The Ball Drop Test as a Rapid Method of Measuring the CBR" *Tech. Translations*, Vol 7, No. 10, p 789 (1962).
110 ASAI, S, "Measurements of Bearing Capacity of Subgrade by Drop Impact Method" *Applied Mech Review*, Vol. 14, No. 9, p 697 (1961).
111 DUNAGEN, W. M, "A Method of Determining the Constituents of Fresh Concrete." *Proc Amer. Conc Inst.*, Vol. 26, pp. 202-210 (1930).
112. MURDOCK, L. J., "The Determination of the Proportions of Concrete." *Cement and Lime Manufacture*, Vol. 21, pp 91-96 (1948).
113 KIRKHAM, R. H. H., "Analysis of Fresh Concrete." *Conc. and Construction Eng.*, Vol. 54, No. 9, p. 44 (1949).
114. *CHADDA, L. R., "The Rapid Determination of Cement Content in Concrete and Mortar." *Indian Conc. J.*, Vol. 29, No. 8, pp. 258-260 (1955).
115 COVAULT, D., and POOVEY, C. E, "The Use of Neutron Activation to Determine Cement Content of Portland Cement Concrete." *HRB Bull. 340* (1962) pp 1-29.
116. *HIME, W. G., and WILLIS, R. A., "Method of Determination of Cement Content of Plastic Concrete." *ASTM Bull. No. 209*, pp. 37-43 (Oct 1955).
117 *"Proposed Tentative Method of Test for Cement Content of Freshly Mixed Concrete." Subcommittee III-c of ASTM Committee C-9, *ASTM Bull. No. 239*, pp. 48-49 (July 1959).

118 *WALKER, S., BLOEM, D. L., GAYNOR, R. D., and WILSON, J. R., "A Study of the Centrifuge Test for Determining the Cement Content of Fresh Concrete." *Materials Research and Standards*, Vol. 1, No. 6, pp 454-460 (June 1961).

119. *BUTLER, B. C., "Development of Instrumentation for Measuring Water and Cement Content of Fresh Concrete." *Report No. EES 206-1*, Eng. Experiment Station, Ohio State Univ. (July 1963).

120. CLEGG, G., "Apparatus for Determining the Water Content of a Concrete Mix." *U.S. Patent No. 2,581,-950* (Jan. 8, 1952).

121 "New Instrument Tests Concrete Mix; Water-Cement Ratio Found Electrically." *Eng. News-Record*, Vol. 150, No. 25, p. 51 (June 11, 1953).

122. *PAWLIW, J., and SPINKS, J. W. T, "Neutron Moisture-Meter for Concrete." *Canadian J. Tech.* (Ottawa), Vol 34, pp. 503-513 (1957).

123. "Test for Air Content of Freshly Mixed Concrete by the Pressure Method." ASTM Designation C 231-62 *ASTM Standards*, Part 10 (1964).

124 KLEIN, W. H., and WALKER, S., "A Method for Direct Measurement of Entrained Air in Concrete." *Proc. Amer. Conc. Inst.*, Vol. 42, pp. 657-668 (1946).

125. MENZEL, C. A, "Development and Study of Apparatus and Methods for the Determination of the Air Content of Fresh Concrete." *Proc. Amer. Conc Inst.*, Vol 43, pp. 1053-1072 (1947).

126. TREMPER, B., and GOODING, W. L., "Washington Method of Determining Air in Fresh Concrete." *Proc. HRB*, Vol. 28 (1948) pp. 210-216.

127 "Test for Air Content of Freshly Mixed Concrete by the Volumetric Method." ASTM Designation C 173-58, *ASTM Standards*, Part 10 (1964).

128. *GRIEB, W. E., "The AE-55 Indicator for Air in Concrete." *HRB Bull. 176* (1958) pp. 23-27.

129. MATHER, B, "Discussion of paper by W. E. Grieb on 'The AE-55 Indicator for Air in Concrete.'" *HRB Bull 176* (1958) pp. 27-28.

130. *NEWLON, H. H., JR., "A Field Investigation of the AE-55 Air Indicator." *HRB Bull. 305* (1961) pp. 1-13.

131. PIGMAN, G. L., "A Vacuum Method of Measuring the Air Content of Fresh Concrete." *Proc. Amer Conc. Inst.*, Vol. 38, pp. 121-132 (1942).

132. *ERLIN, B., "Air Content of Hardened Concrete by a High-Pressure Method." *J Portland Cement Assn.*, Vol. 4, No. 3, pp. 24-29 (Sept. 1962).

133 *LINDSAY, J. D., "Illinois Develops High-Pressure Air Meter for Determining Air Content of Hardened Concrete." *Proc. HRB*, Vol. 35 (1956) pp. 424-433.

134. VERBECK, G. J., "The Camera Lucida Method for Measuring Air Voids in Hardened Concrete." *Proc Amer. Conc. Inst.*, Vol. 43, pp. 1025-1040 (1947).

135 REXFORD, E. P., "Discussion of paper by Verbeck, 'The Camera Lucida Method for Measuring Air Voids in Hardened Concrete.'" *Proc. Amer. Conc. Inst.*, Vol. 43, pp. 1040-1-FF-1040-5 (1947).

136. BROWN, L. S., and PIERSON, C. U., "Linear Traverse Techniques for Measurement of Air in Hardened Concrete." *Proc. Amer. Conc. Inst.*, Vol. 47, pp 117-124 (1951).

137. WARREN, C., "Determination of Properties of Air Voids in Concrete." *HRB Bull. 70*, pp. 1-10 (1953).

138. *KELLY, J. W., and HAAVIK, N. E., "A Single Test for Consistency of Concrete." *ASTM Bull No. 163*, pp 70-74 (Jan. 1950).

139 HOWARD, E. L., and LEAVITT, G., "Kelly Ball vs. Slump Cone—Comparative Tests of Samples Taken at Travis Air Base." *Proc. Amer. Conc Inst*, Vol. 48, pp. 353-356 (1952).

140. *KELLY, J. W., and POLIVKA, M, "Ball Test for Field Control of Concrete Consistency." *Proc. Amer. Conc. Inst.*, Vol. 51, pp 881-888 (1955)

141. *MARR, R. A., JR., and GRIEB, W. E., "Use of the Kelly Ball as a Device for Measuring the Consistency of Concrete." *Pub Roads*, Vol. 28, No. 12, pp. 266-270 (Feb 1956).

142 "Report on Test of Concrete Carried out with Vebe Apparatus." *Report No. 1, Svenska Cementforening*, Teknıska Medelande oek Vender-Sokningstapporter, Malmo, Sweden.

143. CORDON, W, "Evaluation of Concrete and Mortar Mixes." *Proc. Amer. Conc. Inst.*, Vol. 56, pp. 569-580 (1960)

144. *HUGHES, B P., "Development of an Apparatus to Determine the Resistance to Segregation of Fresh Concrete." *Civil Eng. and Pub. Works Review* (London), Vol. 56, No. 658, pp. 633-634 (May 1961).

145. *POLATTY, J. M., "New Type of Consistency Meter Tested at Allatoona Dam." *Proc. Amer. Conc. Inst.*, Vol. 46, pp. 129-136 (1950)

146. POPOVICS, S., "Relation Between the Change of Water Content and the Consistency of Fresh Concrete." *Mag of Conc. Research* (London), Vol. 14, No. 41, pp 92-108 (July 1962).

147. ABRAMS, D. A., "Design of Concrete Mixtures." *Bull. No. 1*, Structural Materials Research Lab., Lewis Inst, Chicago (Dec. 1918).

148. GILKEY, H. J., "Water-Cement Ratio versus Strength—Another Look." *Proc. Amer. Conc. Inst.*, Vol. 57, pp. 1287-1312 (1961).

149 WALKER, S, ET AL, "Discussion of paper by H. J. Gilkey on 'Water-Cement Ratio versus Strength—Another Look.'" *J. Amer. Conc. Inst.*, Vol. 57, pp. 1851-1878 (1961).

150. *MEYER, R. C., "Dynamic Testing of Concrete Pavements with the Soniscope." *Proc. HRB*, Vol. 31 (1952) pp. 234-245

151. *WESCHE, K., "Some Applications of Ultrasonics in Concrete Testing" *Building Science Abstracts*, Vol. 28, No. 11, p. 322 (Nov. 1955).

152. *BULLOCK, R. E., and WHITEHURST, E. A, "Effect of Certain Variables on Pulse Velocities through Concrete." *HRB Bull. 206* (1959) pp. 37-41.

153 JONES, R., "Testing of Concrete by Ultrasonic-Pulse Techniques," *Proc. HRB*, Vol. 32 (1953) pp. 258-275.

154 POWERS, T. C., "Measuring Young's Modulus of Elasticity by Means of Sonic Vibrations" *Proc ASTM*, Vol. 38, Part II (1938).

155. *MEYER, R, "Eight Years of Pulse Velocity Tests on Concrete Pavements in Kansas" *HRB Bull. 206* (1959) pp. 31-36.

156. LAMB, D. R, "A New Soniscope—The 'Elastiscope.'" *Proc. HRB*, Vol. 35 (1956) pp. 418-423

157. KAPLAN, M. F, "Effects of Age and Water-Cement Ratio upon the Relation Between Ultrasonic Pulse Velocity and Compressive Strength of Concrete." *Mag. of Conc. Research* (London), Vol. 11, No. 32, pp. 85-92. (July 1959)

158. WHITEHURST, E. A, "Pulse-Velocity Techniques and Equipment for Testing Concrete" *Proc. HRB*, Vol 33, (1954) pp. 226-241.

159. *"Effects of Concrete Characteristics on the Pulse Velocity—A Symposium" *HRB Bull. 206* (1959) pp 1-74.

160. *KOZAN, G. R, "Non-Destructive Testing of Concrete Pavements." *Proc. HRB*, Vol. 34 (1955) pp. 368-375

161. SCHMIDT, E., "A Non-Destructive Concrete Tester." *Concrete*, Vol. 59, No. 8, pp. 34-35 (Aug 1951).

162. *KOLEK, J, "An Appreciation of the Schmidt Rebound Hammer" *Mag. of Conc. Research* (London), Vol 10, No. 28, pp. 27-37 (Mar. 1958).

163. "Rapid Testing of the Hardness of Concrete" *E.P.A Digest 812*, No. 8, pp. 99-100 (Aug. 1956).

164. *GREEN, G. W., "Test Hammer Provides New Method of Evaluating Hardened Concrete." *Proc. Amer Conc Inst*, Vol. 51, pp. 249-256 (1955).

165. *ZOLDNERS, N. G., "Calibration and Use of Impact Test Hammer," *Proc. Amer. Conc. Inst.*, Vol. 54, pp 161-168 (1958).

166. *MITCHELL, L J, and HOAGLAND, G. G., "Investigation of the Impact-Type Concrete Test Hammer." *HRB Bull. 305* (1961) pp. 14-27.

167. *GRIEB, W. E., "Use of Swiss Hammer for Estimating Compressive Strength of Hardened Concrete" *Pub. Roads*, Vol 30, No. 2, pp. 45-52 (June 1958).

168. *KING, J. W. H., "An Accelerated Test for the Seven and Twenty-Eight Day Compressive Strengths of Concrete" *J. Applied Chemistry*, Vol. 10, No. 6, pp 256-262 (June 1960).

169. "An Accelerated Test for Cement." *Conc and Constructional Eng* (London), Vol. 54, No. 10, pp. 323-324 (Oct. 1959).

170. ORDMAN, N. N. B., and BONDRE, N. G., "Accelerated Curing Tests on Concrete." *Eng.* (London), Vol 185, No. 4798, pp. 243-245 (Feb. 21, 1958).

171 *MALHOTRA, V. M., ZOLDNERS, N. G, and LAPINAS, R, "Accelerated Test for Determining the 28-Day Compressive Strength of Concrete." *Mines Branch Research Report R-134*, Dept. of Mines and Tech. Surveys, Ottawa (Oct. 1964).

172. *"An Accelerated Test for Cement" *Concrete and Const. Eng.* Vol 54, No. 10, pp. 323-324 (Oct. 1959). Also, *Report No. 188*, Swiss Fed. Lab. for Testing Materials, Zurich.

173 GRIEB, W. E, and WERNER, G., "Comparison of the Splitting Tensile Strength of Concrete with Flexural and Compressive Strengths." *Pub Roads*, Vol. 32, No. 5, pp. 97-106 (Dec. 1962).

174. *"New Road Test Device Described." *Colorado Info.*, Col. Goods Roads Assn, Vol 18, No. 12, p. 6 (Mar 22, 1956).

175. *MAXON, G, "Suggested Quality Control Method for Highway Concrete." *Roads and Streets*, Vol. 99, No. 7, pp 72, 74, 78 (July 1956).

176. GRANT, E. L., "The Economic Relationship Between Design and Acceptance Specification." *STP No. 103*, ASTM, pp. 3-12 (1949).

177 SHOOK, J. F., "Significance of Test Results Obtained from Random Samples." *STP No. 362*, ASTM, pp 13-28 (1963)

178. ABDUN-NUR, E. A., "Discussion of paper by J. F Shook on Significance of Test Results Obtained from Random Samples." *STP No. 362*, ASTM, pp. 29-30 (1963).

179. ASTM, "Manual on Quality Control of Materials." *STP No. 15-C*, pp. 128-134 (1951).

180. U S. DEPARTMENT OF DEFENSE, "Sampling Procedures and Tables for Inspection by Attributes. *Military Standard No. 105B* (Dec 31, 1958)

181. U S. DEPARTMENT OF DEFENSE, "Sampling Procedures and Tables for Inspection by Variables for Percent Defective" *Military Standard No 414* (June 11, 1957)

182 DUNCAN, A. J., *Quality Control and Industrial Statistics* Rev. ed., Richard D. Irwin, Inc. (1959).

183. GRANT, E. L, *Statistical Quality Control* 3rd ed, McGraw-Hill (1964).

184 LEIBERMAN, G. J, and RESNIKOFF, G J, "Sampling Plans for Inspection by Variables." *J. Amer Statistical Assn*, Vol. 50, No 270 (June 1955).

185 IRICK, P., "Basic Concepts of Statistical Quality Control." *Proc 50th Ann. Road School*, Purdue Univ., pp. 25-38 (Mar. 1964).

186. MILLER-WARDEN ASSOCIATES, "Effects of Different Methods of Stockpiling Aggregates." NCHRP Project 10-3 *Interim Report*, pp. 9-11 (1964).

187. ADAMS, C M., JR, and HARDWAY, G. A, "Fundamentals of Laser Beam Machining and Drilling" *Trans Inst. Electrical and Electronic Eng.*, Vol. IGA-1, No. 2, pp. 90-96 (Mar -Apr. 1965)

188 EPPERSON, J. P., DYER, R. W., and GRZYWA, J C, "The Laser Now a Production Tool." *The Western Electric Eng.*, Vol 10, No. 2, pp. 9-16 (Apr. 1966)

189. MERRILL, H. J, "Laser Progress and Applications." *Proc 1962 Army Science Conf.*, West Point, N. Y., pp 89-102 (Aug 28, 1962). Also, NASA *Report N62-17507.*

190 "Lasers Move into the Marketplace." *Business Week*, pp. 90-103 (Sept. 10, 1966).

191. "Laser Welding and Machining." *Eng. Proc. P-44*, Penn. State Univ. (May 1966)

192 "Laser May be Hard-Rock Tunneler" *Eng. News-Record*, p. 19 (Dec. 1, 1966).

193 Tyner, H. L., "An Evaluation of Conventional and Nuclear Methods for Determining *In-Situ* Density and Moisture Content of Soils" Thesis, Dept. of Civil Eng, Clemson Univ. (May 1966)

194. Schwartz, A. E., "Phase Two Final Report, Rapid Means of Determining Density and Moisture Content of Soils and Granular Materials" Dept of Civil Eng, Clemson Univ. (Jan. 1967)

195. Gioiosa, T. E., "A Rapid Method for Determining the In-Place Density of a Pavement Base Course by a Drop Hammer Penetrometer." Thesis, Dept of Civil Eng., Clemson Univ. (Dec. 1965).

196 South Carolina State Highway Department, *Standard Specifications for Highway Construction.* (1964)

197. Barkan, D. D., *Dynamics of Bases and Foundations* McGraw-Hill (1960).

198 Dobrin, M. B., *Introduction to Geophysical Prospecting.* McGraw-Hill (1960).

199 Ewing, W. M., Jardetsky, W. S, and Press, F, *Elastic Waves in Layered Media.* McGraw-Hill (1957).

200 Ferry, J D., *Viscoelastic Properties of Polymers.* John Wiley (1961).

201 Kolsky, H, *Stress Waves in Solids.* Clarendon Press, London (1953).

202. McMaster, R C., et al, "Development of Sonic and Ultrasonic Power Devices for Application in Highway Engineering." First Annual Report, *Transp Eng. Report No 221-1,* Eng. Experiment Station, Ohio State Univ. (Oct 15, 1963).

203. Hertwig, A, Fruh, G, and Lorenz, H., "Die Ermittlung der fur das Bauwesen wichtigsten Eigenschaften des Boden durch erzwungene Schwingunge." *Veroffentlichungen des Instituts der Deutschen Forschungsgesellschaft fur Bodenmechanik* (Degebo), Tech. Hochschule Berlin, Part 1, Julius Springer (1933).

204. Hertwig, A., "Die Anwendung dynamischer Baugrunduntersuchungen" *Veroffentlichungen des Instituts der Deutschen Forschungsgesellschaft fur Bodenmechanik* (Degebo), Tech. Hochschule Berlin, Part 4, Julius Springer (1936)

205. Sung, T. Y., "Vibrations in Semi-Infinite Solids Due to Period Surface Loading." *STP No. 156,* ASTM (1953).

206. Converse, F. J., *Foundation Engineering.* Chap. 8, "Foundations Subjected to Dynamic Forces," McGraw-Hill (1962).

207. D'Appolonia, E., "Loose Sands—Their Compaction by Vibroflotation." *STP No. 156,* ASTM (1953)

208. Heukelom, W, and Klomp, A. J. G., *Dynamic Testing as a Means of Controlling Pavements.* Ann Arbor (1962).

209. Moavenzadeh, F, and McMaster, R. C., "Potential Uses of Sonic and Ultrasonic Devices in Highway Construction." *NCHRP Report 25* (1966).

210. Nijboer, L. W., and Metcalf, C T., "Dynamic Testing at the AASHO Road Test." *Proc. Internat. Conf. on Struct. Design of Asphalt Pavements,* Ann Arbor (1962).

211 Bernhard, R. K, and Finelli, L., "Pilot Studies on Soil Dynamics." *STP No 156,* ASTM (1953).

212. Fung, Y. C., *Foundations of Solid Mechanics.* Prentice-Hall (1965).

213 Owens, R. J., "An Investigation of a Vibratory Method for Compaction Control of Crushed Stone." Thesis, Dept. of Civil Eng., Clemson Univ. (Dec. 1966).

214. Natrella, M. G., "Experimental Statistics." *National Bureau of Standards Handbook 91,* p. T-82 (1963).

215. Turner, C. H., "Chart Method Gives Unit Weight of Crushed Base Stone." *Roads and Streets,* Vol. 97, No 12, pp. 62-63 (Dec. 1954).

216. Hertz, H. *Annalen der Physik,* Vol. 36, No. 1 (1888).

217 Maxwell, J. C., *A Treatise on Electricity and Magnetism* Vol II, Clarendon Press, Oxford (1892).

218. Stone, J. M., *Radiation and Optics.* Chap. 19, McGraw-Hill (1963).

219. Wiebelt, J. A., *Engineering Radiation Heat Transfer* Chap. 1, Holt, Reinhart, & Winston (1966).

220. Andrews, C L, *Optics of the Electromagnetic Spectrum.* Chap 16, Prentice-Hall (1960).

221. von Hippel, A., *Dielectrics and Waves.* Wiley, pp. 82-91 (1954).

222. Birks, J. B., *Modern Dielectric Materials.* Heyward and Co, London, pp. 17-20 (1960).

223. Rostron, J. P., Schwartz, A. E., and Brown, F. B., "Air Gap Procedure for the Measurement of Density with Gamma Ray Backscatter Technique," *Hwy Res. Circ. No. 44* (Aug. 1966).

224 McGonnagle, W, and Park, F., *International Science and Technology.* (July 1964).

225. Davis, B. R., Lipscombe, E. B., and Knight, S. S., "Terrain Analysis by Electromagnetic Means." *Tech. Report No. 3-693,* U S. Army Eng Waterways Exper Station, Vicksburg, Miss. (Oct. 1965).

226. Maley, D. R, "Applied Research to Establish Infrared Detection Methods for Nondestructive Analysis of Metallic and Ceramic Structures." *Pub. No. AD-299230P,* U.S. Dept. of Commerce (Jan. 1963)

APPENDIX A

MOISTURE CONTENT DETERMINATION

Two field methods for determination of moisture content were evaluated in this study: (1) the alcohol burning method, and (2) the calcium carbide gas pressure method (Speedy moisture tester). Both of these methods were evaluated in the field and were found to be accurate, inexpensive, and reasonably rapid (*193*). Because some question had arisen regarding the applicability of the Speedy method to soils of high clay content, a series of laboratory tests was performed with this device. A similar series of laboratory tests using comparable soil samples was carried out using the alcohol burning method. In addition to determining the accuracy and precision of the alcohol burning method, efforts were made to determine the best sample size, amount of alcohol, and number of burnings required for this moisture test.

ALCOHOL BURNING METHOD

A large number of soil samples ranging in clay content from 4 percent to 71 percent were used to evaluate the alcohol burning method for moisture content determination. Relatively large samples (500 to 1,000 gm) can be used in this test method if large granular material is present in many of the samples. However, the samples used in the laboratory study were entirely fine-grained soils, thus, such large sample sizes were found unnecessary. An average sample size of 200 gm was used for the alcohol burning test and a similar sample size was used for the oven-dry control test

Initially, typical sandy, silty, and clayey soils were used in determining the optimum amount of alcohol and minimum number of burns required for accurate moisture content determination The amount of alcohol required was found to be a function of soil moisture, whereas the number of burnings required depended on clay content as well as moisture content A minimum of 1 oz of alcohol per 100 gm of soil was required for sandy soils Clay soils at extremely high moisture contents required 2 oz of alcohol per 100 gm of sample Thus, most conditions could be satisfied with 1½ oz of alcohol per 100 gm of soil Because the sample size used in the evaluation was 200 gm, 3 oz of alcohol were used for all tests.

In the preliminary studies none of the moisture content samples significantly changed weight after three burnings for several soil-alcohol ratios. Test data were therefore accumulated using three burnings for each sample. Moisture content calculations were made after each burning and compared to the oven-dried moisture content. The results of these tests are given in Table A-1 and shown in Figures A-1, A-2, and A-3.

For relatively dry soils (5 percent moisture content or less), Figure A-1 indicates that one burning would be sufficient. Figure A-2 shows that for moisture content determination the coefficient of correlation between oven-dried moisture content and that determined by two burnings is 0.997, with a standard error of estimate of ±0 36 percent for moisture contents between 0 and 20 percent. For higher moisture contents, three burnings are required and, as shown in Figure A-3, for moisture contents up to 35 percent a coefficient of correlation of 0.999 and standard error of estimate of ±0.42 percent were obtained. Thus, in both instances moisture contents were obtained by the alcohol burning procedure well within ±1 percent (95 percent confidence level) of oven-dried moisture contents The regression equation relating the predicted oven-dried moisture contents, ω_{od}, and alcohol burning moisture contents, ω_{ab}, for two burnings is·

$$\omega_{od}\ (\text{percent}) = 0\ 09 + 1.004\ \omega_{ab} \qquad \text{(A-1)}$$

For three burnings the regression equation is:

$$\omega_{od}\ (\text{percent}) = -0.37 + 1\ 013\ \omega_{ab} \qquad \text{(A-2)}$$

In each case the plot of the regression equation (see Figs. A-2 and A-3) is nearly identical with the line of equal values.

CALCIUM CARBIDE GAS PRESSURE METHOD

The results of the Speedy moisture tester measurements are given in Table A-2. Thirty-five soil samples, with clay contents up to 71 percent, were used in this evaluation study. Each soil sample was mixed with varying amounts of water to provide a range of moisture contents. After the soil and water were thoroughly mixed, one part was placed in the drying oven (105°C) for the comparative moisture content.

The pressure gauge on the Speedy apparatus is calibrated in percent moisture content based on sample wet weight. However, soil moisture is usually specified with respect to dry weight. The relationship between these two moisture contents is given by the equation:

$$\omega = \frac{\omega'}{1 - (\omega'/100)} \qquad \text{(A-3)}$$

in which

ω = percent moisture content, dry weight basis; and
ω' = percent moisture content, wet weight basis.

If sufficient time is allowed for the gas generated in the Speedy tester to reach equilibrium, then the reading, R, is simply substituted for ω' in Eq A-3. On the other hand, the tester can be calibrated for a specific time interval, such as 1 min or 3 min. In this instance the relationship between moisture content and gauge reading is:

$$\omega = \frac{C\ (R)}{1 - (R/100)} \qquad \text{(A-4)}$$

TABLE A-1

ALCOHOL BURNING METHOD LABORATORY DATA

Sample			Test Results			
Number	Percent Clay	AASHO Class	Oven-Dried Moisture Content	Alcohol Burning Moisture Content: One Burn	Two Burns	Three Burns
243-A	4	A-3(0)	4.3	4.4	4.5	4.5
			10.3	10.4	10.5	10.7
			13.4	12.9	13.9	14.0
11-C	6	A-2-4(0)	3.3	2.7	2.9	3.2
			5.8	5.1	5.2	6.0
			9.3	7.1	8.7	9.0
			14.9	11.6	14.0	14.1
			23.0	11.4	21.7	22.5
43-C	8	A-5(1)	5.5	4.9	5.8	6.3
			10.6	7.7	10.7	11.4
			16.0	10.0	16.5	17.1
			24.4	11.8	22.9	24.7
			36.1	12.7	31.2	37.0
202-A	11	A-2-4(0)	9.0	8.4	8.9	9.0
			16.9	14.5	16.9	16.9
			13.5	12.4	13.4	13.5
133-A	18	A-4(0)	8.3	7.8	8.2	8.6
			16.7	13.3	16.6	17.0
			25.1	18.3	25.0	25.4
			33.2	8.5	29.5	34.0
181-A	23	A-4(1)	6.5	5.9	6.3	6.5
			13.0	10.5	12.6	12.9
			22.9	13.7	22.4	23.0
			32.2	9.3	26.7	31.0
			36.9	10.3	29.9	36.0
243-C	26	A-2-4(0)	9.0	8.8	9.2	9.7
			19.1	15.0	19.3	19.4
			28.8	11.7	27.8	29.1
			37.2	6.6	26.6	38.1
12-B	29	A-4(3)	11.5	10.1	11.2	11.6
			12.8	11.8	12.9	13.0
			19.6	14.9	19.6	19.7
			32.9	13.2	29.9	32.4
203-C	35	A-7-6(6)	18.5	14.8	17.8	18.1
			25.4	15.7	23.9	24.6
			11.9	10.5	11.6	12.0
			30.9	12.0	28.7	30.4
			38.2	8.3	24.8	35.6
212-B	39	A-7-6(9)	7.8	7.3	7.3	8.0
			17.1	13.0	16.5	17.1
			26.5	14.0	26.0	26.7
			36.1	10.2	30.1	36.1
31-B	43	A-7-5(10)	11.3	10.2	11.3	11.8
			16.3	13.5	16.2	16.7
			21.3	14.9	20.7	21.2
			24.7	15.0	24.0	24.8
			29.4	16.6	28.3	29.4
81-C	45	A-7-6(18)	13.5	11.4	13.5	13.9
			23.8	15.7	22.7	23.4
			34.2	15.6	30.5	33.6
			41.8	8.5	31.8	40.5
			5.6	4.9	5.6	6.0
183-B	48	A-7-6(15)	9.3	8.8	9.4	9.7
			20.1	15.6	19.6	19.9
			27.4	12.8	26.4	27.2
			36.9	9.7	29.9	36.3
172-B	52	A-7-5(14)	16.9	12.5	16.7	17.6
			23.0	12.5	21.3	23.0
			29.0	14.9	27.6	29.6
			35.0	13.1	29.7	35.2
			41.7	14.4	33.1	41.0
201-B	55	A-7-5(6)	7.4	6.6	7.3	7.6
			14.5	11.7	14.5	14.[illegible]
			20.8	14.9	21.2	21.6
			27.7	15.2	26.5	27.8
			31.3	14.5	28.8	31.6
232-B	66	A-7-5(20)	19.6	14.3	19.0	19.8
			23.9	17.8	23.0	23.9
			28.8	19.1	27.6	28.9
			33.6	13.5	30.2	33.7
			36.8	15.6	33.2	36.5
203-B	71	A-7-5(20)	15.7	12.3	15.6	18.2
			27.9	18.0	26.6	[illegible]
			42.5	15.9	36.0	41.7

in which

ω = percent moisture content, dry weight basis;
R = Speedy moisture tester gauge reading; and
C = calibration factor.

Previous researchers (*83*) have recommended that at least 3-min readings be used to allow sufficient time for the reaction between the soil moisture and the calcium carbide reagent. These investigators further comment that the Speedy apparatus should be calibrated for regional soils and that the calibration curve for one tester may not apply to another apparatus. In view of these recommendations, the average calibration factor, C, was determined for 3-min readings and found to be 0.97. Thus, for the apparatus used in these studies, oven-dried moisture content is related to gauge reading by the equation:

$$\omega = \frac{0.97\, R_3}{1 - (R_3/100)} \qquad \text{(A-5)}$$

in which R_3 is the 3-min gauge reading.

The calibration factor calculated from the curve previously published (*83*) and supplied by the manufacturer for 3-min readings was 0.96, whereas the factor for 1-min readings was 0.94 for moisture contents between 5 and 30 percent. The calibration curve plotted from Eq. A-5 is shown in Figure A-9.

Figure A-4 shows the correlation between the oven-dried moisture content and the moisture content calculated from Eq A-5 using the Speedy moisture tester gauge readings. The average error, or difference, between the control moisture content and the corrected Speedy results was 0.1 percent moisture content for the 183 moisture tests.

Two calculations were made from the test results. The error, or difference, between the moisture determinations was first obtained by subtracting the oven-dried moisture content from the Speedy results as corrected by Eq. A-5. Then, the percent error was calculated by expressing the error as a percentage of the oven-dried moisture content. Figure A-5 shows the percentage of the total tests that deviated from equal values for a specific amount of error. Ninety-nine percent of the tests were within 6 percentage units of moisture content, whereas 90 percent of these tests were within 2 percentage units of moisture content. Figure A-6 shows the distribution of the percent error based on oven-dried moisture content. Ninety-three percent of the tests deviated by less than 10 percent, whereas 71 percent deviated by less than 5 percent of the oven-dried moisture content.

Studies also were made to determine whether the accu-

TABLE A-2

LABORATORY CALIBRATION OF SPEEDY MOISTURE TESTER

Sample			Test Results				
Number	Percent Clay	AASHO Class	Control Moisture Content %	Gage Reading	Speedy Moisture Content %	Error	Percent Error
243-A	4	A-3(0)	5.86	5.80	5 91	+0 05	+0.9
			10.78	10 40	11.16	+0.38	+3.5
			15.59	14.70	16.54	+0 95	+6.1
			20.61	18.40	21.65	+1.04	+5.0
11-C	6	A-2-4(0)	6.79	6 44	6 60	-0 19	-2.8
			11 70	10 79	11.62	-0.08	-0.7
			16.69	13.50	15 00	-1.69	-10.1
			20.54	18 38	21 63	+1 09	+5.3
43-C	8	A-5(1)	14 44	13 62	15 14	+0.70	+4.8
			18 71	17 19	19 92	+1.21	+6.5
			22 15	19 70	23.54	+1.39	+6.3
			25 32	22.00	27 08	+1.76	+7 0
			31 11	25.90	33.58	+2.47	+7 9
			33.62	27.40	36 25	+2 63	+7 8
			37 19	29 56	40 29	+3 10	+8.3
202-A	11	A-2-4(0)	6 32	6.40	6 57	+0.25	+4 0
			11.35	10 70	11 50	+0 15	+1.3
			16 21	14 40	16.16	-0 05	-0.3
			21 15	17 90	20 94	-0.21	-1 0
243-B	14	A-2-4(0)	6 00	6 00	6.12	+0.12	+2.0
			11 04	10.40	11 16	+0.12	+1.1
			15 84	13.90	15.50	-0.34	-2.1
			21 16	17.20	19 95	-1.21	-5 7
133-A	18	A-4(0)	6.14	5 62	5.72	-0.42	-6.8
			9 56	8 99	9 48	-0 08	-0.8
			13 59	12 65	13.90	+0.31	+2 3
			17 23	15.78	18.00	+0.77	+4 5
			20 79	17 98	21 05	+0.26	+1.3
			25 07	20 90	25 36	+0 29	+1 2
			28 50	24 00	30 33	+1 83	+6 4
			33 08	26 38	34 39	+1 31	+4.0
			35 36	27 90	37 17	+1.81	+5 1
181-A	23	A-4(1)	12 03	10 70	11 50	-0.53	-4 4
			17.20	14 95	16 88	-0 32	-1 9
			21 77	18 50	21 81	+0 04	+0 2
			27 01	22 40	27 72	+0 71	+2 6

Sample			Test Results				
Number	Percent Clay	AASHO Class	Control Moisture Content %	Gage Reading	Speedy Moisture Content %	Error	Percent Error
243-C	26	A-2-4(0)	5.84	5.82	5.92	+0.08	+1.4
			10 70	10.12	10.82	+0.12	+1.1
			15 46	14.42	16.19	+0.73	+4.7
			19.87	17.60	20.52	+0.65	+3.3
12-B	29	A-4(3)	6.51	5.99	6.12	-0.39	-6.0
			10.08	9.52	10.10	+0.02	+0.2
			14.20	13 25	14.67	+0.47	+3.3
			17.66	16.23	18.62	+0.96	+5.4
			21.89	19.58	23.38	+1.49	+6.8
			26.89	23.12	28 88	+1.99	+7 4
			29.94	25.50	32.85	+2.91	+9.7
203-C	35	A-7-6(6)	13.25	11.70	12.72	-0 53	-4.0
			29 08	20.90	25.34	-3.74	-12.8
			28.95	23.20	28.99	+0.04	+0.1
212-B	39	A-7-6(9)	12.65	11 90	12.97	+0.32	+2.5
			17.34	14.90	16.80	-0.54	-3.1
			22.73	19.60	23.42	+0.69	+3.0
			27.69	22.20	27.41	-0.28	-1.0
31-B	43	A-7-5(10)	7.22	6 75	6.95	-0.27	-3.7
			12.43	11.60	12.60	+0.17	+1.4
			17.13	15 60	17.76	+0.63	+3.7
			22.43	19.00	22.51	+0.08	+0 4
81-C	45	A-7-6(18)	7.65	6.90	7.11	-0.54	-7.1
			12.65	11.10	11.99	-0.66	-5.2
			17 65	15.65	17 84	+0.19	+1.1
			22.12	18.80	22.22	+0.10	+0.5
183-B	48	A-7-6(15)	12 60	11.40	12.35	-0.25	-2.0
			17.51	15.20	17.21	-0.30	-1.7
			22.38	19 10	22.68	+0.30	+1.3
			27.89	22.90	28.49	+0 60	+2.2
172-B	52	A-7-5(14)	12 76	11.40	12 35	-0.41	-3.2
			17.91	15.40	17.47	-0.44	-2.5
			22 61	18.80	22.25	-0.36	-1.6
			27.83	22 70	28.22	+0.39	+1.4

Sample			Test Results				
Number	Percent Clay	AASHO Class.	Control Moisture Content %	Gage Reading	Speedy Moisture Content %	Error	Percent Error
I-20 (413.50)	56	A-7-5	5.48	5.20	5.26	-0.22	-4.0
			10.16	9.81	10.44	+0.28	+2.8
			14.30	13 40	14.86	+0.56	+3.9
			19.45	15.90	18.16	-1.29	-6.6
			22.80	20.04	24.08	+1.28	+5.6
			28.82	23.80	30.00	+1.18	+4.1
			30.50	25.72	33.22	+2.72	+8.9
			38.46	29.04	39.26	+0.80	+2.1
			40.92	30.76	42.62	+1.70	+4.2
S.H.S.#1			8.75	8.30	8.69	-0.06	-0.7
			13.60	11.75	12.64	-0.96	-7.1
			18.45	16.10	18.43	-0.02	-0.1
			23.50	17 40	20.21	-3.29	-14.0
			28.69	18.80	22.22	-6.47	-22.6
			33.54	23.40	29.33	-4.21	-12.6
S H.S.#2			6 96	7.00	7.31	+0.35	+5.0
			11.20	10.65	11.44	+0.24	+2.1
			15.58	14.05	15.71	+0.13	+0.8
			22.95	20 05	24.07	+1.12	+4.9
Purysburg #1	15	A-2-4	11.09	10.45	11.21	+0.12	+1.1
			18.94	16 10	18.43	-0.51	-2.7
			26.99	22.10	27.26	+0.27	+1.0
CCC #1	9	A-2-4	17.24	15.95	18.22	+0.98	+5.7
			24.84	21.10	25.68	+0.84	+3.4
Union Bag #5	18	A-2-4	10.60	9.39	9.94	-0.66	-6.2
			18.13	16.39	18.83	+0.70	+3.9
			26 40	21.00	25.54	-0 86	-3.3
I-20 (626-628)	13	A-2-4	9.68	9 35	9.90	+0.22	+2.3
			17.52	15.70	17.89	+0.37	+2.1
			25 61	21.00	25.54	-0.07	-0.3
			33.15	22.30	27.58	-5.57	-16.8
I-20 (638)	6	A-3	9.18	8.92	9.43	+0.25	+2.7
			16.94	15.75	17 96	+1.02	+6 0
			24.76	20.40	24.58	-0.18	-0.7
			31.61	25.40	32.69	+1.08	+3.4

Sample			Test Results				
Number	Percent Clay	AASHO Class.	Control Moisture Content %	Gage Reading	Speedy Moisture Content %	Error	Percent Error
201-B	55	A-7-5(6)	13.28	12.02	13.12	-0.16	-1.2
			17.26	13.37	14.88	-2.38	-13.8
			22.99	20.40	24.60	+1 61	+7.0
			25.78	21.56	26.40	+0.62	+2.4
232-B	66	A-7-5(20)	9.86	8.50	8.92	-0.94	-9.5
			14.17	12.75	14.04	-0.13	-0.9
			19.63	16.80	19.39	-0.24	-1.2
			24.85	20 40	24.60	-0.25	-1.0
203-B	71	A-7-5(20)	14.88	12.70	13 99	-0.89	-6.0
			19.78	16.30	18.72	-1.06	-5.4
			24.62	20.40	24.60	-0.02	-0.1
			29.30	24.20	30.67	+1.37	+4.7
I-20 (365)		A-2-6	6.19	6.00	6.12	-0.07	-1.1
			10.28	9.80	10.44	+0.16	+1.6
			14.08	12.20	13.32	-0.76	-5.4
			17 89	16.30	18.70	+0 81	+4.5
			21.89	18.40	21.65	-0.24	-1.1
			26.03	20.90	25.40	-0.63	-2.4
			29.71	21.80	26.77	-2.94	-9.9
Bin #1			10.89	11.21	12.13	+1.24	+11.4
			16.04	15.20	17.19	+1.15	+7.2
			22.68	19.00	22.53	-0.15	-0.7
			25.06	21.00	25 54	+0.48	+1.9
			31.92	24.80	31.68	-0.24	-0.8
			25.77	21.30	26.00	_0.23	+0.9
			40.46	29.60	40.42	-0.04	-0.1
			45.86	30.40	41.95	-3.88	-8.5
			43.32	31.60	44.38	+1.06	+2.4
Bin #2			10.11	9 30	9.84	-0.27	-2.7
			15.08	14.05	15.69	+0.61	+4.0
			20.01	17.50	20.36	+0.35	+1.7
			25.23	21.00	25.54	+0 31	+1.2
			30.50	24.80	31.68	+1.18	+3.9
			35 14	27.30	36.04	+0.90	-2.6
			40.90	30.80	42.74	+1.84	+4 5
			45.90	32.20	45.60	-0.30	-0 7
			50 94	33.20	47.73	-3.21	-6.3

TABLE A-2 (*Continued*)

Sample			Test Results				
Number	Percent Clay	AASHO Class.	Control Moisture Content%	Gage Reading	Speedy Moisture Content%	Error	Percent Error
Bin #3			15 69	14 00	15 63	-0.06	-0 4
			20.42	17.10	19.80	-0.62	-3.0
			24.36	20.05	24.08	-0 28	-1 1
			30 46	24 70	31 49	+1.03	+3 4
			35.98	26 50	34.63	-1 35	-3.8
			41.14	30.40	41.95	+0 81	+2 0
			46 42	32.00	45 26	-1.16	-2.5
			52 30	35.00	51 68	-0.62	-1.2
			55.47	35 00	51 68	-3 79	-6.8
I-20 (520)		A-7-6	5 34	5 18	5.25	-0.09	-1.7
			9.27	9 20	9 72	+0 45	+4.9
			13.08	12 65	13.90	+0.82	+6.3
			17.15	15 60	17 73	+0.58	+3 4
			21 12	18 60	21 94	+0 82	+3 9
			27.67	22.50	26.91	-0.76	-2.7
			32.98	25.30	32 54	-0.44	-1.3
I-20 (404 50)	33	A-6	5 38	4.85	4.90	-0.48	-9.0
			9 54	9 00	9.49	-0 05	-0 5
			13 75	12.20	13.33	-0 42	-3.1
			17.55	15 55	17 69	+0.14	+0.8
			21.88	19.20	22.80	+0.92	+4.2
			26 00	21.20	25 82	-0.18	-0.7
			29.40	20.86	25.32	-4.08	-13 9
			33 90	24 76	30 75	-3 15	-9 3
I-20 (638)	34	A-4(3)	6.22	5 35	5.43	-0.79	-12.7
			11 91	10 83	11 68	-0 23	-1 9
			14 38	13 02	14 39	+0 01	+0 1
			19 75	17 78	20.76	+1 01	+5 1
			23 77	20 44	24.69	+0 92	+3.9
			26 41	22.02	27 14	+0.73	+2.8
			34 08	27 10	35 69	+1 61	+4 7
			35 80	27 46	36.35	+0.55	+1 5
			39 46	29 22	39.65	+0 19	+0.5
I-20 (639)	5	A-1-6	13.24	12 50	13.73	+0.49	+3 7
			21.00	17 60	20.50	-0 50	-2 4
			28.87	19 40	23.09	-5 78	-20 0
			36.61	22 60	28.05	-8 56	-23.4
Okeetee #3	13	A-2-4	18 03	16 45	18 91	+0 88	+4.9
			23.45	20.80	25.20	+1 75	+7 5
			28 63	23 50	29 47	+0 84	+2.9
			34 30	26 30	34.32	+0.02	+0 1

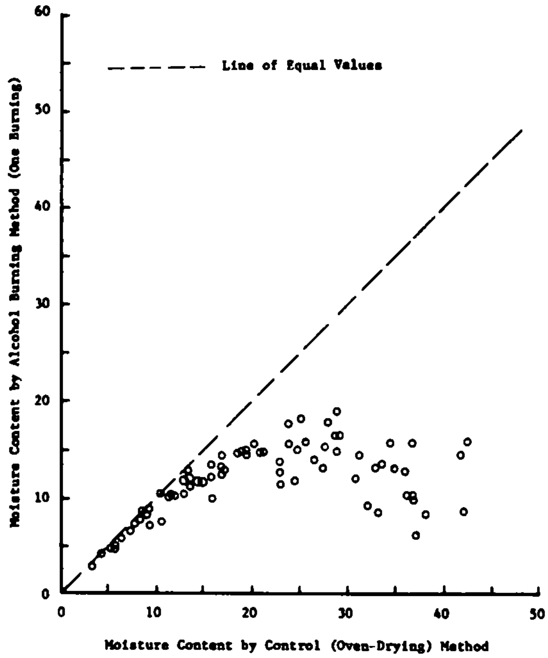


Figure A-1 Correlation between control (oven-drying) method and alcohol burning method for moisture content determination in laboratory tests

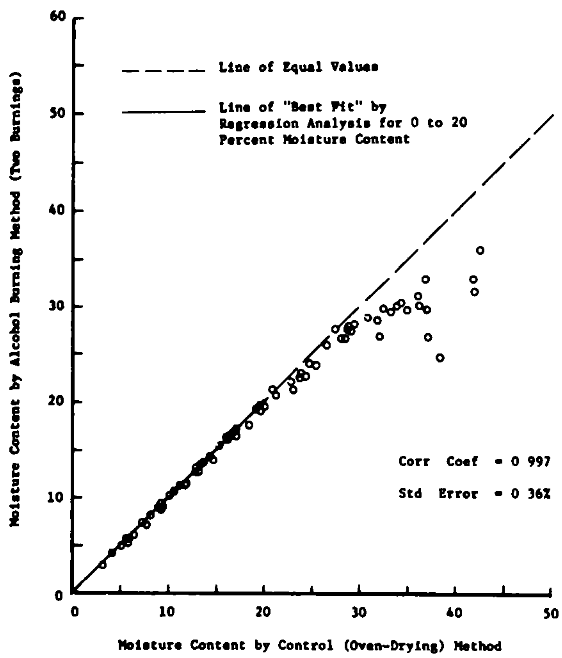


Figure A-2 Correlation between control (oven-drying) method and alcohol burning method for moisture content determination in laboratory tests

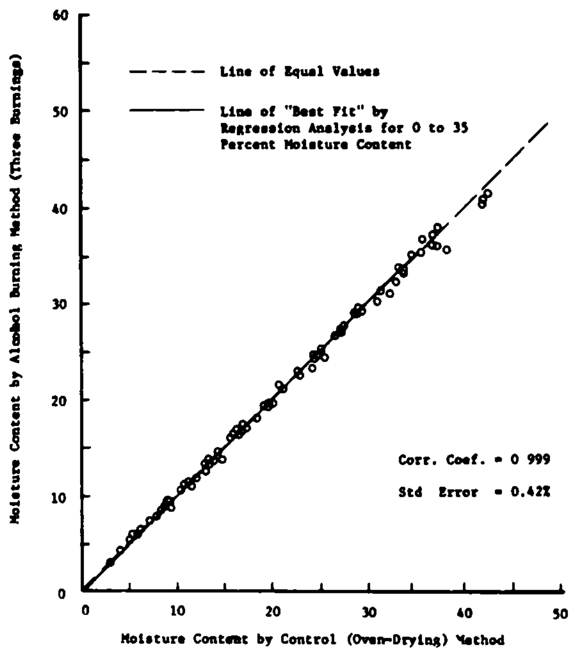


Figure A-3 Correlation between control (oven-drying) method and alcohol burning method for moisture content determination in laboratory tests

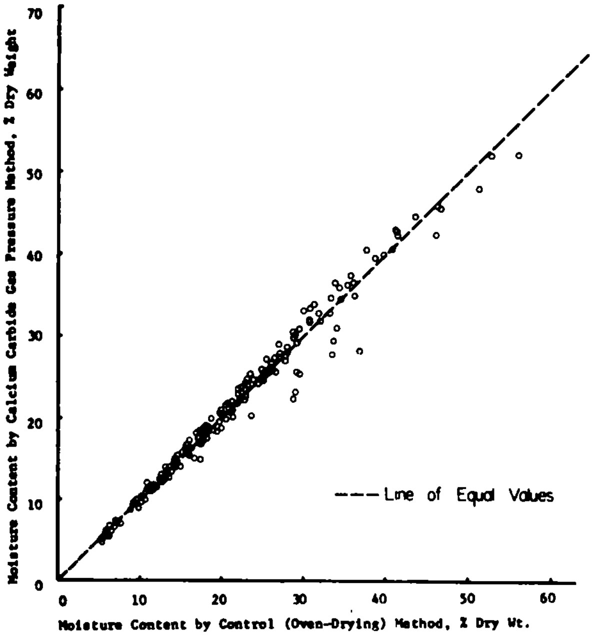


Figure A-4 Correlation between control (oven-drying) method and calcium carbide gas pressure method for moisture content determination in laboratory tests.

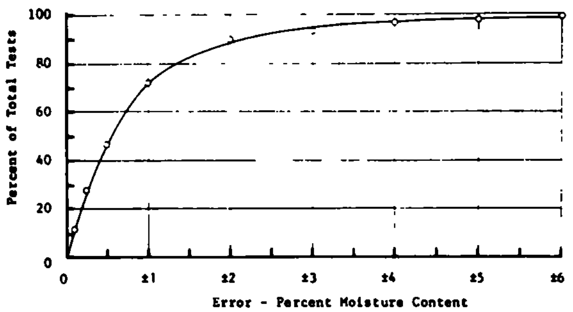


Figure A-5 Distribution of error between Speedy moisture tester results based on oven-dried moisture content.

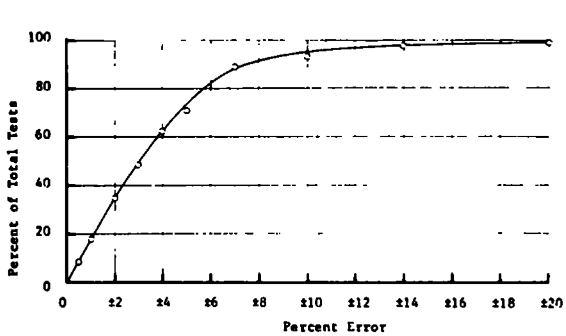


Figure A-6. Distribution of percent error of Speedy moisture tester results based on oven-dried moisture content.

racy of the Speedy results was adversely affected by either high clay contents or high moisture contents. The calibration curve given by Eq. A-5 and shown in Figure A-9 was used to determine moisture content for all of these samples regardless of clay content. The resulting data are shown in Figures A-7, A-8, and A-10 As shown in Figures A-7 and A-8, neither the error nor percent error appear to be a function of clay content for the soils tested which contained as much as 71 percent clay. Accuracy of the Speedy tester was likewise not affected by moisture contents, as shown in Figure A-10. Precision of the method, however, decreased somewhat at moisture contents between 24 and 35 percent.

RECOMMENDED FIELD PROCEDURES

Alcohol Burning Method

Purpose

The purpose of the alcohol burning test is to determine an accurate estimate of oven-dried (105°C) moisture content of soil or granular material.

Sample Size

A sample of 150 gm to 250 gm is sufficient for accurate moisture content determination of fine-grained soils (90 to 100 percent passing the No. 4 sieve). For granular materials the sample size will depend on the size of the largest particles; however; 600 gm to 1,000 gm normally will be sufficient.

Quantity of Alcohol

Methyl alcohol (methanol) is used in this test method. The amount of alcohol depends on the sample size, the amount of clay, and the moisture content. For most soils 1½ oz of alcohol per 100 gm of sample is sufficient. For soil with high clay contents and high moisture contents an additional ounce or two may be necessary to ensure initial ignition of the alcohol-soil mixture. No increase in alcohol quantity is necessary for the second burning.

Procedure

The following procedure is recommended for determination of moisture content:

1. Weigh to nearest 0.1 gm approximately 200 gm of soil in a suitable, lightweight metal pan (sample size should be increased if soil contains a significant amount of grains larger than No. 4 sieve size).

2 Add 1½ oz of methanol per 100 gm of sample and allow to soak for 1 min; ignite and stir frequently to prevent a crust from forming on the surface of the sample.

3. Allow sample to cool approximately 10 to 15 min (cooling time may be shortened if pan containing sample is floated in water).

4. Measure out a second charge of methanol and pour quickly over cooled sample.

5. Repeat step 2 and allow to cool approximately 5 min after burning is completed before weighing.

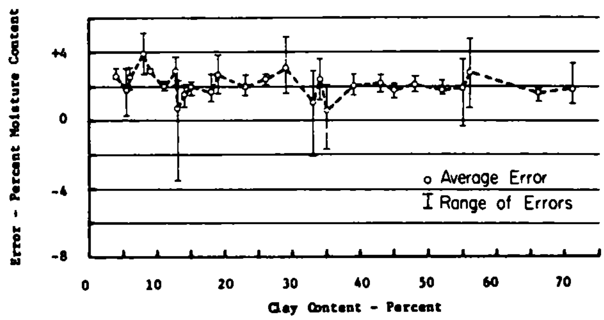


Figure A-7 Difference (error) between Speedy moisture tester results and oven-dried moisture content for soils containing clay

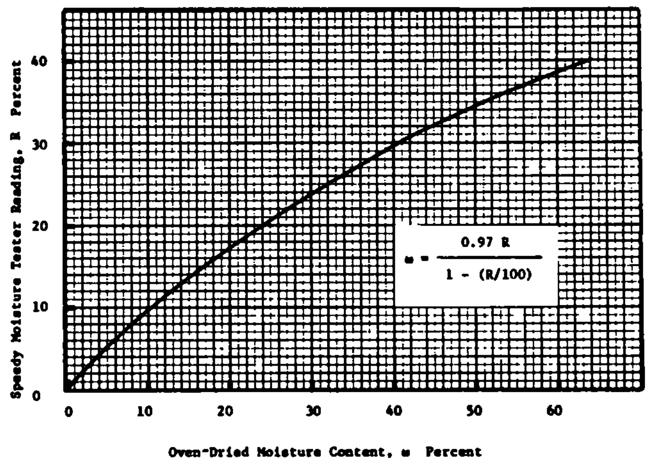


Figure A-9. Speedy moisture tester calibration curve for 3-min readings

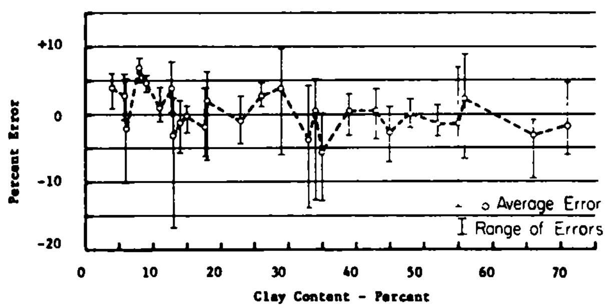


Figure A-8. Percent error (based on oven-dried moisture content) of Speedy moisture tester results for soils containing clay

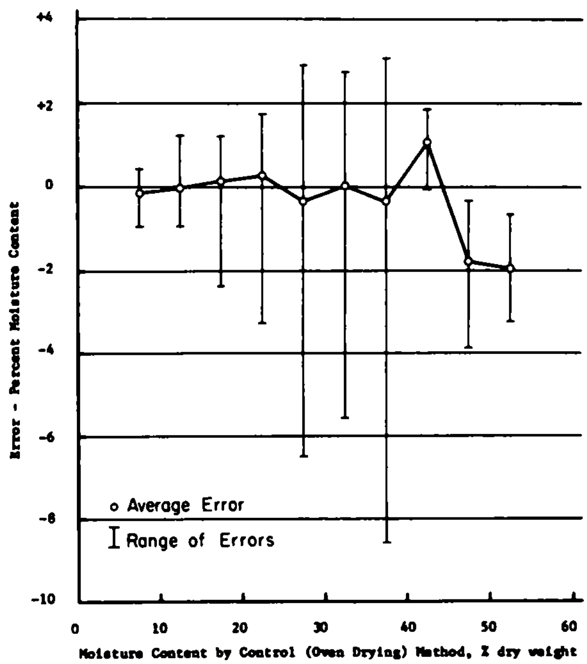


Figure A-10. Difference (error) between Speedy moisture tester results and oven-dried moisture content for soils containing varying amounts of water

6. Weigh sample to nearest 0.1 gm and calculate percent moisture as follows:

$$\text{Percent moisture} = \frac{(\text{Wet weight} - \text{Dry weight})}{(\text{Dry weight} - \text{Pan weight})} \times 100$$

7. If percent moisture as calculated by the foregoing equation is greater than 20 percent, repeat steps 4 through 6.

Precautions

Methanol should never be poured onto a sample from a large container. After measuring out the correct amount, quickly pour the methanol into the sample pan from a wide-mouth jar or beaker. Slow application of the methanol results in rapid evaporation, causing some of the fines in the sample to be carried off with the rising vapors. Too much methanol will cause sandy soils to sputter and jump out of the pan as the sample is heated. This problem is only slight with silts and nonexistent with clays.

If the sample is too hot when weighed, air currents will develop and cause inaccurate readings. If the sample is allowed to stand more than 5 or 10 min after burning is completed, the soil will pick up hygroscopic moisture unless dry climatic conditions prevail.

Equipment Required

1 aluminum loaf pan (approx. 4 in. × 8 in. × 3 in.);
1 measuring cup (16-oz capacity);
1 balance (accurate to 0.1 gm);
1 long-handled stirring rod (steel);
1 pr insulated gloves;
1 small propane torch for igniting sample (optional); and
5 gal methanol (methyl alcohol); replace as needed.

Calcium Carbide Gas Pressure Method

Purpose

To determine an accurate estimate of oven-dried (105°C) moisture content of fine-grained soils.

Sample Size

The larger of two sizes of a commercial apparatus (Speedy moisture tester) is recommended for use in this test procedure. Thus, the sample size required is 26 gm for moisture contents less than 24 percent and 13 gm for moisture contents greater than 24 percent.

Procedure

The procedure is essentially the same as recommended by Blystone et al. (*83*) for the 26-gm-size moisture tester.

1. Thoroughly clean tester and cap using a brush to clean the bomb and a cloth to clean the cap.
2. Place three measures (approximately 22 gm) of calcium carbide (reagent) and two 1¼-in. steel balls in the large chamber of the moisture tester. If the material being tested is clean granular material (no clay or silt) the steel balls may be omitted.
3. Using the tared scale, weigh a 26-gm sample of soil. If the moisture content of the 26-gm sample exceeds the limit of the pressure gauge, a half-size sample (13 gm) is used, the percentage indicated on the dial is then doubled.
4. Place the soil sample in the cap, then, with the pressure vessel in a horizontal position, insert the cap in the pressure vessel and tighten the clamp to seal the cap to the unit.
5. Raise the moisture tester to a vertical position so the soil in the cap falls into the pressure vessel.
6. Holding the moisture tester horizontally, manually rotate the device for 10 sec so that the steel balls are put into orbit around the inside circumference, and then rest for 20 sec. Repeat the shake-rest cycle for a total of 3 min. Do not allow the steel balls to fall against either the cap or the orifice leading to the dial, because this might cause damage
7. With the tester held horizontal read the pressure gauge after the needle stops moving. Determine the moisture content of the soil on a dry-weight basis by referring to the calibration curve (Fig. A-9) or the equation of this curve given on the chart.

Precautions

After each test examine the cap and sample. If any soil remains in the cap or if lumps are found in the sample, obtain another sample and re-run the test. It is essential to thoroughly clean the instrument after each test. Extreme caution should be taken when cleaning the instrument because the dust is highly irritating to the eyes, nose, and throat, and gas generated in the reaction is explosive if released near an open flame or cigarette.

Because the sample to be tested is relatively small, care must be taken to obtain a representative soil sample. Scales and pressure gauge should be checked periodically.

Equipment required

1 Speedy moisture tester—large (26-gm) size;
1 tared balance;
1 cleaning brush;
reagent (several cans), and
cleaning cloths (several).

APPENDIX B

DETERMINATION OF SOIL DENSITY USING A LOW-FREQUENCY VIBRATION TECHNIQUE

The control of compaction by methods employing dynamic attenuation was determined to be theoretically feasible on the basis of a review of literature. Both low-frequency vibratory devices and ultrasonic devices are considered potentially useful as rapid means of evaluating degree of compaction. In this appendix a brief review of the theory of vibrating systems precedes test results from experiments employing a small vibrator that was tested for its applicability in determining rapidly the unit weight of compacted soils.

ANALYSIS OF VIBRATING SYSTEMS

In general, any material body will exhibit elastic, inertia, and damping forces when acted on by external forces. The spring-mass-dashpot model has been used by many investigators to assist the description of this behavior. Work by Hertwig, Früh, and Lorenz (*203*) and reports of the Deutsche Forschungsgesellschaft für Bodenmechanik (Degebo) (German Research Society for Soil Mechanics) (*204*) indicated that a lumped parameter model as shown in Figure B-1 can be used as a first approximation to the behavior of a soil body. The governing equation for this model is:

$$F(t) = m\frac{d^2y(t)}{d\,t^2} + C\frac{dy(t)}{dt} + Ky(t) \qquad \text{(B-1)}$$

in which

m = mass of vibrating body;
$F(t)$ = forcing function;
C = coefficient of viscous response;
K = coefficient of elastic response, and
$y(t)$ = displacement.

The Degebo vibrator (*203*) consisted of counter-rotating weights that were synchronized during rotation so that the horizontal components of centrifugal force produced by the rotating weights cancelled. The resulting force was unidirectional and could be used in the model of Figure B-1, in which motion of the mass is characterized by one degree of freedom.

The dynamic force generated by this vibrator is given by:

$$F(t) = m\,r\,\omega^2 \sin \omega t \qquad \text{(B-2)}$$

in which

$F(t)$ = dynamic force or forcing function;
m = mass of the rotating weights;
r = eccentricity of the rotating weights;
ω = angular velocity of the rotating weights; and
t = time.

If the vibrator is in continuous contact with the soil, Eqs. B-1 and B-2 can be equated. It should be noted that m, as given in Eq. B-1, includes the weight of the vibrating soil McMaster et al. (*202*) show that, for transducers continuously connected to vibrating materials, force and power input can be related. Sung has used Hertwig's data (*204, 205*) to relate power input to the geometric properties of a Degebo type of vibrator with a circular base.

The energy of the forcing function and the work accomplished by the vibrator will vary with different densities of soil. The work accomplished by a vibrator powered by an electric motor can be related to electrical units of energy and work. Hence, a wattmeter or an ammeter can be used to obtain an estimate of the total power input. If power losses due to friction within the vibrator are determinable, then the power absorbed by the vibrating material can be interpreted directly from the ammeter readings.

Because it is normal practice in highway construction control to specify unit weight of the compacted soil, it would be desirable to solve Eq. B-1 for the mass, m, which can be related to unit weight by the relationship:

$$m = \frac{(\text{wt. of vibrator}) + (\text{volume of soil})\ (\gamma\ \text{soil})}{g} \qquad \text{(B-3)}$$

However, assuming that C and K are known, the problem remains indeterminate because the volume of soil affected is not known. If the volume of soil affected by the vibrations is known or can be determined by some auxiliary means, then the unit weight of the soil can be evaluated. Pauw (*206*) assumed that the configuration of the volume of soil affected by the vibrator was trapezoidal and equated the kinetic energy of the plate that vibrated in contact with the soil and the kinetic energy of the soil and plotted the apparent or affected mass of the soil versus the size of the loaded plate.

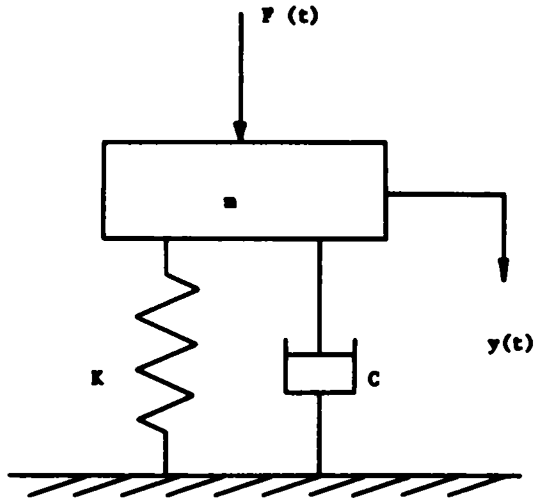


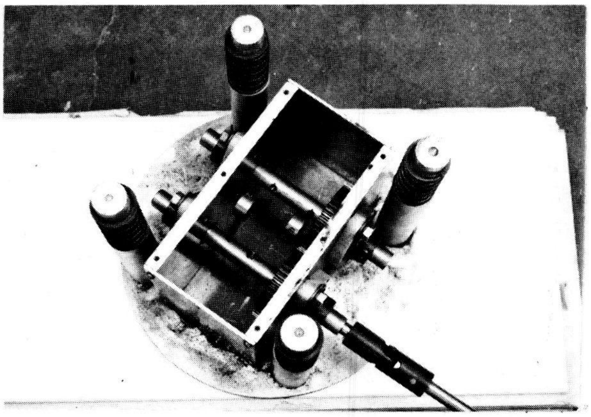
Figure B-1. Spring-mass-dashpot model of vertically oscillating soil mass.

Although it is not possible to make an absolute evaluation of unit weight without untenable simplifying assumptions, a vibrator-soil mass model may provide a relative indication of how compaction is progressing. Relationships between input energy, as measured by electrical current, and unit weight are used in vibroflotation practice (*207*) and in evaluating the dynamic properties of polymers and elastomers by means of forced oscillations (*200*).

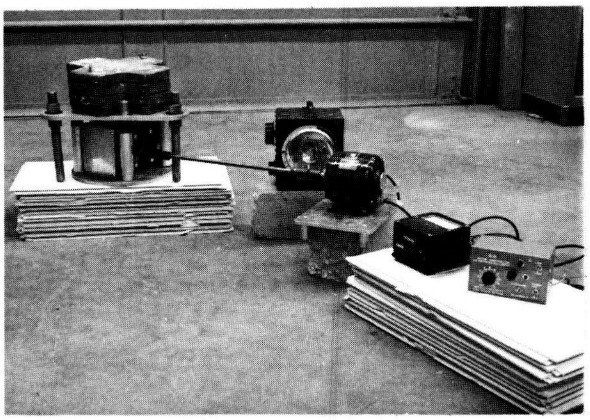
It was recognized that complex conditions such as varying moisture content and soil type might preclude the use of vibration attenuation methods in assessing degree of compaction in different soil types; however, these methods may be of use in situations where these complex conditions are not present In addition to this, evaluation of other parameters, such as C or K, the coefficients of viscous and elastic response, without consideration of the affected mass, may provide information about soil damping and stiffness characteristics that could be incorporated into construction specifications. Theoretically, structure-sensitive properties which may change independent of unit weight could also be represented by these parameters.

Converse (*206*) has recommended that compaction of soils by vibration can be optimized by vibrating at frequencies close to resonant frequency. It is believed that operating a vibrator at frequencies other than resonant will give a more accurate indication of the unit weight of the soil in situ without significant densification of the soil. Hence, it was planned to evaluate degree of compaction without locating resonant frequencies. Several references (*207-211*) give details concerning the design, performance, and potential use of vibratory devices in highway construction evaluation.

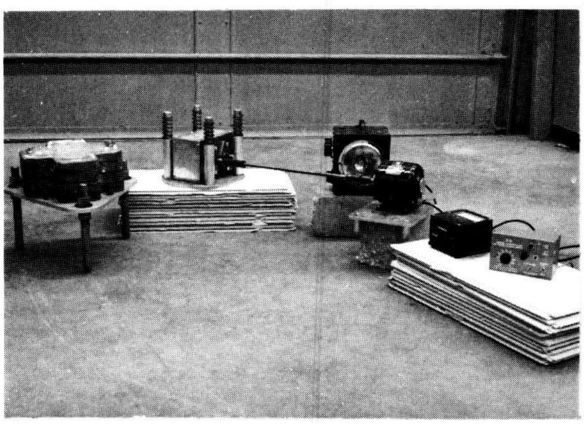
High-frequency oscillations have been used to evaluate material properties of elastic as well as viscoelastic materials. Several references (*197-201*) indicate that the



(a) Internal View of Vibrator Showing Timing Gears and Eccentric Weights



(b) Test Set-up on Celotex Sheets



(c) Surcharge Platform Removed from Vibrator

Figure B-2. Equipment used for evaluation of dynamic alternation procedure (motor control, ammeter, drive motor, stroboscope, and vibrator).

energy of waves propagated by oscillations can be related to the amplitude of the oscillation as well as the distance from the wave source. Ferry (*200*) and Barkan (*197*) present expressions for energy attenuation and wave propagation in various media which show the functional dependence of attenuation and propagation on the mass of the medium transmitting the oscillations. Waves passing through soil can be measured and recorded with the proper instruments placed on or below the surface. The propagation of Rayleigh and Love waves is well-documented in the literature (*199*). The development of the ultrasonic equipment used in this project was motivated by these principles.

EVALUATION OF A LOW-FREQUENCY VIBRATOR

A small vibrator, shown in Figure B-2a, was used together with the appurtenances shown in Figures B-2b and B-2c to measure the dynamic attenuation of compacted soils. The power input to the vibrator was determined by measuring the armature current of the drive motor. To apply the analysis previously described it was essential that the vibrator remain in contact with the supporting material. This was accomplished by placing 200 lb of lead weights on the platform shown in Figure B-2b. Four springs transferred this weight from the platform to the vibrator. The legs of the platform were adjustable in height so that the total force holding down the vibrator could be regulated.

The vibrator was operated by placing the device on the supporting material and then regulating the speed of the drive motor until a specific amount of current passed through the armature of the motor. The frequency of the vibrator in revolutions per minute was measured for several levels of armature current for each support condition. Figure B-2b shows the test set up for the dynamic attenuation procedure. The supporting material used for these tests was 12 × 24 × ½-in. Celotex sheets. Sheet material was selected so that the damping coefficient and spring constant could be changed simply by increasing or reducing the total thickness of material that supported the vibrator. These sheets were placed on a concrete floor for which displacement under the vibratory load was considered negligible compared to that of the Celotex sheets.

The vibrator was operated at frequency intervals such that the drive motor was supplied with armature currents ranging from 0.3 amp to 1.2 amp. The motor control was fused for 1.8-amp maximum current and the maximum no-load speed of the drive motor was approximately 4,000 rpm. Table B-1 gives the resulting frequencies of the vibrator for various armature currents and total thicknesses of Celotex sheets. The column indicating 0-in. thickness gives the frequency obtained with the vibrator resting on the concrete floor. The maximum vibratory frequency obtained for each total thickness of Celotex sheets is approximately equal to the frequency necessary to produce resonance. Current and speed limitation prevented operation of the vibrator at frequencies greater than those required for resonance.

The relationship between vibrator frequency and power input (armature current) is shown in Figure B-3. For

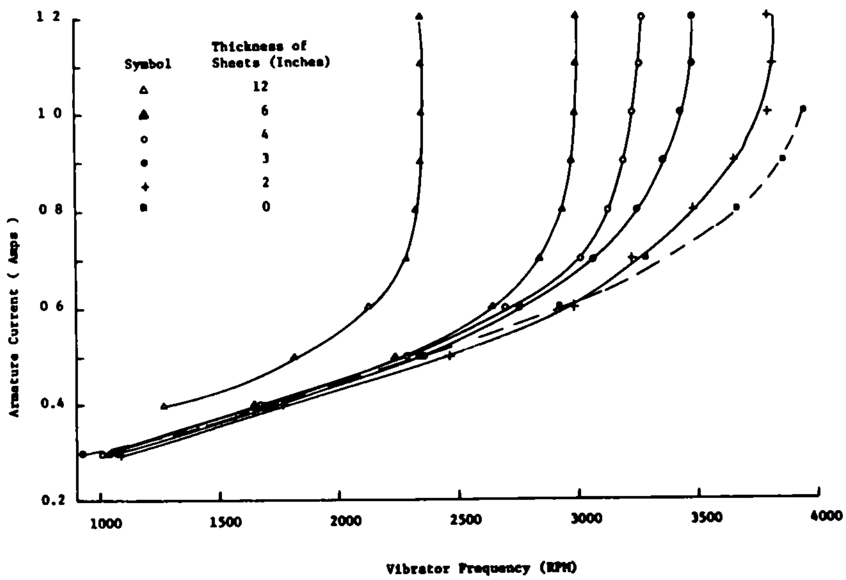


Figure B-3 Vibrator frequency versus armature current for various total thickness of Celotex sheets

each thickness of supporting material there is a threshold frequency below which the relationship of armature current to vibrator frequency is essentially independent of the total thickness of the sheets Beyond this threshold speed the vibrator and supporting material approach resonance and power demand increases rapidly as the vibratory frequency is increased.

The relative modulus of subgrade reaction (coefficient of elastic response) was calculated for each thickness of Celotex sheets such that the modulus for the maximum total thickness, 12 in., was given a value equal to one. Correspondingly, the modulus for the minimum total thickness, 2 in, has a value of six. The relationship between the relative modulus of subgrade reaction and frequency of the vibrator at various levels of armature current is shown in Figure B-4. For small currents, below the threshold currents shown in Figure B-3, the frequency of the vibrator is little affected by the dynamic properties of the supporting material As the level of armature current increases, the vibratory frequency approaches resonance and becomes a function of relative subgrade modulus. As resonance is approached the relationship between frequency and relative modulus is nearly independent of armature current. It can be noted from Figure B-4 that the curves defined for 1.0 and 1.2 amp are more sensitive to changes in the relative modulus than are curves defined for lower currents.

The vibrator also was used to determine the unit weight of a silty clay soil on the Clemson University campus The soil was compacted loosely, moderately and firmly; however, differences in armature current were not large enough to provide an accurate indication of the densification of soil in the small increments of unit weight that are encountered in highway construction practice. The results of the tests on the silty clay are shown in Figure B-5.

It was concluded from this phase of the study that low-frequency vibratory devices may have some value when used to measure the relative modulus of subgrade reaction. However, experimental data indicate that the use of this equipment to measure density of compacted and in-situ soils is not practical.

TABLE B-1

VIBRATOR FREQUENCY
FOR VIBRATOR SUPPORTED ON CELOTEX SHEETS
AT VARIOUS POWER INPUTS

ARMATURE CURRENT (AMPS)	VIBRATOR FREQUENCY (RPM) FOR A TOTAL THICKNESS OF CELOTEX SHEETS OF· 12 IN	6 IN.	4 IN.	3 IN	2 IN.	0 IN
0 3	—	1045	1025	1075	1090	930
0 4	1270	1650	1675	1740	1775	1685
0.5	1820	2240	2290	2360	2470	2340
0.6	2130	2645	2700	2760	2990	2920
0 7	2290	2845	3020	3070	3230	3270
0 8	2330	2945	3130	3250	3485	3670
0.9	2350	2980	3200	3360	3660	3870
1.0	2355	2995	3240	3440	3880	3950
1.1	—	—	3270	3485	3825	—
1 2	2355	3000	3280	3490	3800	—

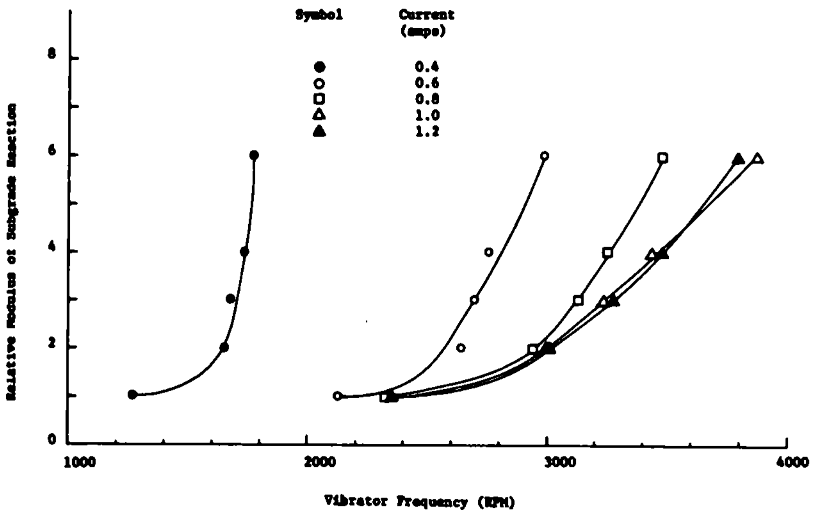


Figure B-4 Relationship between relative modulus of subgrade reaction and speed of rotation at various levels of armature current.

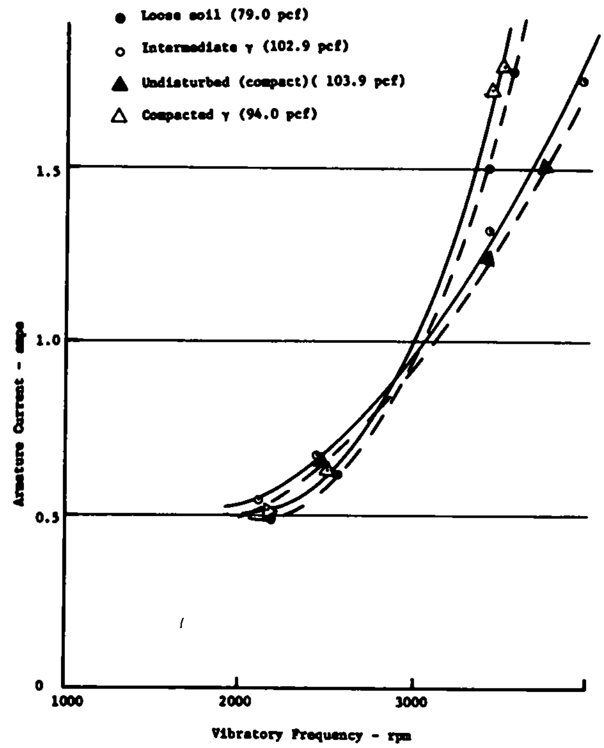


Figure B-5 Current frequency relations for compacted soils.

APPENDIX C

RELATIVE COMPACTION OF GRANULAR MATERIAL

Methods used for the compaction control of granular material include both field and laboratory procedures. All methods, however, require that a sample of material be removed from the roadway and then placed in an appropriate test device. Many attempts have been made to realistically produce confinement and compactive efforts which imitate actual field conditions. Most methods may be categorized as impact procedures, chart and formula methods, vibratory procedures, and compaction of test strips. Owens (*213*) concluded that vibratory compactors produced higher field densities and reached greater depths than did static compaction. Furthermore, both theoretical and empirical relationships have been derived relating the characteristics of the compaction apparatus, in particular the resonant frequency, to the degree of compaction of the material tested.

An in-situ compaction test that would eliminate complexities caused by removal of a sample from a compacted roadway was developed in this portion of the research. A vibratory compactor for field use was used for obtaining representative in-situ control densities because it had been demonstrated that laboratory vibratory procedures had produced densities that were comparable with field densities.

The three variables selected for investigation in this study were as follows: (1) frequency of vibration, (2) time of vibration (duration), and (3) static load (surcharge). A preliminary study was made to determine the effect of each of these variables and their combinations on density. A multiple regression analysis was used to evaluate these effects. Three equally spaced values for each variable were selected; hence, the three variables, with three values for each variable taken three at a time, generated 27 combinations to be used for this analysis. To obtain accurate data, each set of 27 combinations was repeated three times, each replication being one block. The test area was nine test sites square, thus, each block consisted of three rows of nine test sites, or 27 test sites. The combinations of test variables and the level of each variable are shown in Figure C-1.

A standard random numbers table (*214*) was used to determine: (1) the order of testing the blocks, (2) the order of testing rows within each block, and (3) the order of testing combinations of variables within each row.

DESCRIPTION OF COMPACTION DEVICE

The apparatus designed for the in-situ compaction test incorporated both vibratory and static loading. Figure C-2 shows the vibratory compactor used in this study. The dynamic force was provided by an air-driven vibrator located between the two columns in Figure C-2.

The purpose of the compaction device was to transmit vibrations and static loads to the crushed stone on which the device was placed. The compactor consisted of a pneumatically driven vibrator and a load transfer assembly. A hydraulic ram which transferred the desired magnitude of static load to the top bearing plate of the compactor was included as one part of the load transfer assembly. Twelve 1,000-lb concrete blocks which provided the reaction for the static and dynamic loads were supported by a

Blocks								
1			2			3		
Rows			Rows			Rows		
1	2	3	2	3	1	3	1	2
$F_3T_2L_3$	$F_2T_1L_3$	$F_2T_1L_3$	$F_3T_3L_2$	$F_2T_3L_2$	$F_2T_2L_2$	$F_3T_2L_2$	$F_3T_2L_1$	$F_2T_3L_1$
$F_2T_1L_2$	$F_1T_1L_1$	$F_1T_3L_3$	$F_3T_3L_1$	$F_1T_1L_1$	$F_1T_1L_3$	$F_1T_3L_1$	$F_1T_2L_1$	$F_1T_1L_1$
$F_2T_1L_1$	$F_3T_3L_2$	$F_3T_2L_2$	$F_3T_1L_2$	$F_3T_2L_1$	$F_1T_1L_2$	$F_1T_1L_3$	$F_3T_2L_3$	$F_3T_1L_2$
$F_1T_1L_3$	$F_3T_3L_3$	$F_1T_3L_1$	$F_1T_2L_3$	$F_1T_3L_1$	$F_1T_3L_2$	$F_2T_1L_3$	$F_3T_3L_3$	$F_2T_1L_1$
$F_1T_2L_1$	$F_2T_2L_2$	$F_3T_2L_1$	$F_1T_3L_3$	$F_2T_2L_3$	$F_2T_3L_3$	$F_1T_2L_2$	$F_2T_3L_3$	$F_2T_2L_1$
$F_3T_1L_1$	$F_1T_2L_2$	$F_2T_2L_3$	$F_3T_1L_1$	$F_3T_1L_3$	$F_2T_1L_1$	$F_3T_3L_2$	$F_2T_2L_3$	$F_3T_1L_1$
$F_1T_3L_2$	$F_3T_3L_1$	$F_3T_1L_3$	$F_2T_1L_2$	$F_2T_3L_1$	$F_3T_2L_2$	$F_3T_1L_3$	$F_3T_3L_1$	$F_2T_2L_2$
$F_3T_1L_2$	$F_2T_3L_3$	$F_2T_3L_1$	$F_3T_3L_3$	$F_2T_1L_3$	$F_2T_2L_1$	$F_1T_2L_3$	$F_2T_1L_2$	$F_2T_3L_2$
$F_2T_3L_2$	$F_1T_1L_2$	$F_1T_2L_3$	$F_3T_2L_3$	$F_1T_2L_1$	$F_1T_2L_2$	$F_1T_1L_2$	$F_1T_3L_3$	$F_1T_3L_2$

<u>Legend</u>: Frequency-RPM — $F_1 = 1000$, $F_2 = 1250$, $F_3 = 3000$; Time-Seconds — $T_1 = 20$, $T_2 = 40$, $T_3 = 60$; Load-Pounds — $L_1 = 3000$, $L_2 = 6000$, $L_3 = 9000$

Figure C-1. Experimental design for determining the effect of time, frequency, and surcharge on density.

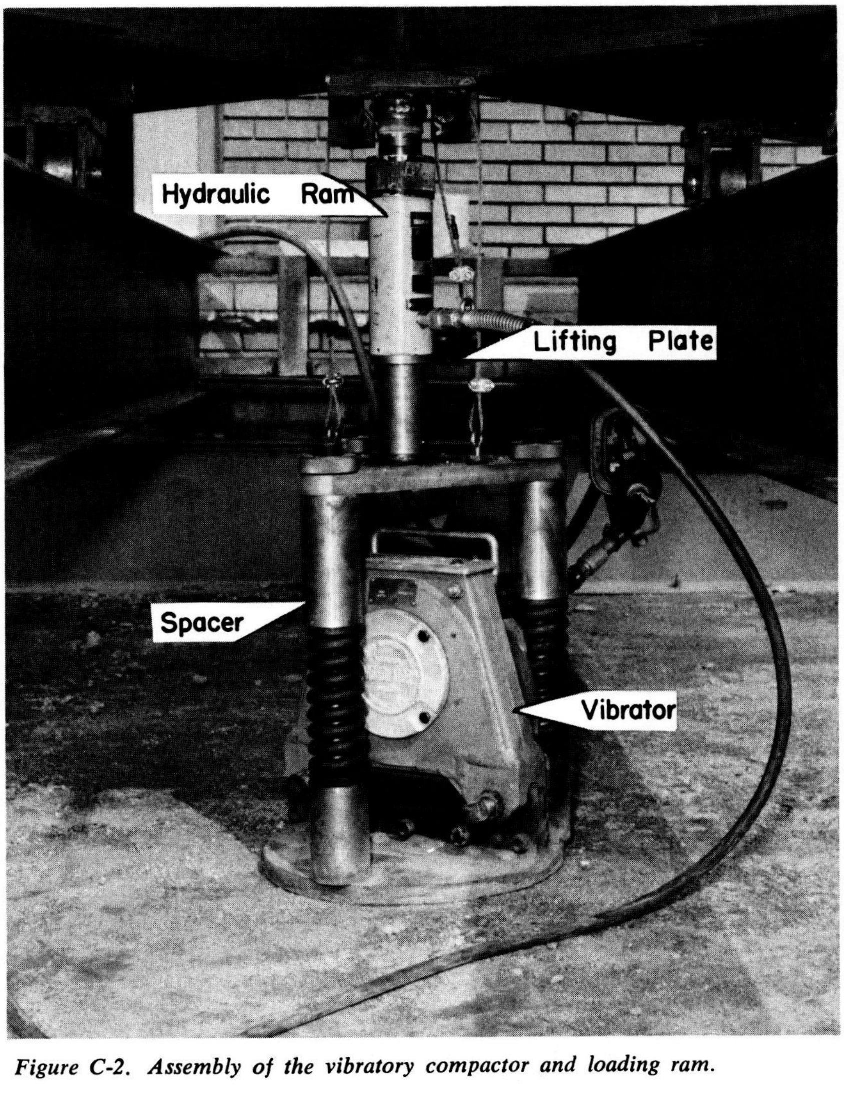


Figure C-2. Assembly of the vibratory compactor and loading ram.

specially designed carriage that could move in an east-west direction on two wide-flange beams, as shown in Figure C-3. The two wide-flange beams were movable in a north-south direction so that it was possible to locate the load carriage anywhere within the 20-ft by 20-ft test area. The Vibrolator, a commercially available vibrator supplied by Martin Engineering Company (Model No. CCVP-3000), was selected for use in this project. The vibrations were induced by the centrifugal motion of an eccentric weight driven by an air motor.

The top bearing plate of the vibrator was modified so that the hydraulic ram could be used to hoist the compaction device.

EFFECT OF TIME, FREQUENCY, AND SURCHARGE ON DENSITY

The test area was prepared by placing approximately 6 in. of crusher-run material on top of a paved parking lot. The material was spread, leveled, and compacted with the gas-powered Wacker tamper. Approximately 18 tons of Type 2 crushed granite-gneiss conforming to South Carolina *Standard Specifications* (*196*) were spread approximately 8 in. deep on top of the crusher-run material. String lines were used to lay off 81 2-ft-square test sites. The moisture content of a specified test row was increased the day before it was to be tested until it was within the optimum range determined from moisture-density relationships (see Fig. C-4). The row to be tested and the row on each side of it were covered with several thicknesses of plastic to minimize moisture loss. The plastic was removed from each test site, one site at a time, and replaced on the site immediately following the compaction process.

The loading ram and vibrator were calibrated prior to testing. The ram was placed in a testing machine and the ram gauge pressure was read for corresponding loads obtained on the testing machine. The vibrator was calibrated by adjusting the air-pressure regulator until the desired frequency was observed with a stroboscope.

After a row of nine tests was completed, the loading trolley and compactor were moved away from the area and the Rainhart volumeter was used to measure the density of the compacted material.

The 81 observations given in Table C-1 were used to determine the coefficients for a multiple regression equation of the form:

$$Y = b_0 + b_1x_1 + b_2x_1^2 + b_3x_2 + b_4x_2^2 + b_5x_1x_2 + b_6x_1^2x_2 + b_7x_1x_2^2 + b_8x_1^2x_2^2 \quad \text{(C-1)}$$

in which

Y = predicted density of crushed stone, in pcf;
x_1 = frequency, in hundreds of rpm;
x_2 = time, in seconds; and
b = regression equation coefficients.

Only the terms that were significant at the 5 percent level * were used in the regression equation. Results obtained from the F-test, which was used to determine the significant terms of the regression model, indicated that the magnitude of the surcharge had no influence on the density resulting from the test procedure. Hence, time and frequency were the only variables that were used in the regression analysis. The coefficients for Eq. C-1 were determined by means of a computer program, with the resulting equation:

$$\begin{aligned} Y = 454.277 &- 57.2478458x_1 + 2.35715160x_1^2 \\ &- 21.2192203x_2 + 0.25389631x_2^2 \\ &+ 3.59055159x_1x_2 - 0.14599808x_1^2x_2 \\ &- 0.042905568x_1x_2^2 + 0.001746484x_1^2x_2^2 \end{aligned} \quad \text{(C-2)}$$

* Level of significance is that probability of getting an F-value greater than the F obtained from the data; where F is equal to the mean square of the variable tested divided by the error mean square.

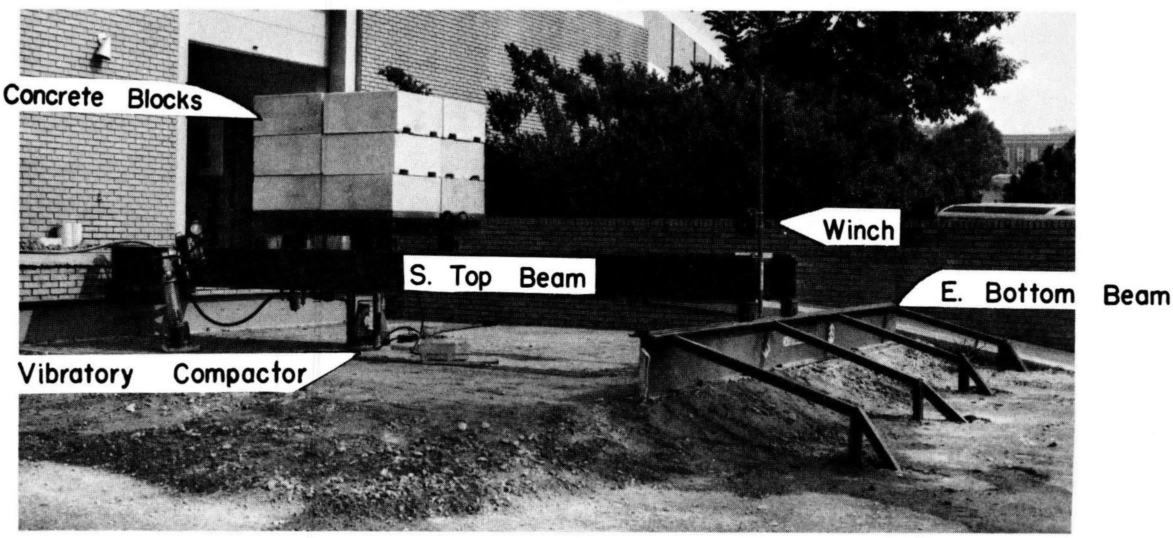


Figure C-3. Test setup for evaluation of compaction test procedure.

TABLE C-1

DENSITY OBSERVATIONS

Combination* of Variables	Density (pcf) Blocks 1	2	3	Average Density (pcf)
F_1 L_1 T_1	121 58	113.89	122 27	119.25
F_1 L_1 T_2	115 83	118 90	11R 43	117 72
F_1 L_1 T_3	113 58	120 82	126 27	120.22
F_1 L_2 T_1	119.65	116 30	123.44	119.80
F_1 L_2 T_2	116.08	121 67	123 88	120 54
F_1 L_2 T_3	120.12	120 02	121 28	120 47
F_1 L_3 T_1	117.67	114 77	121.77	118 07
F_1 L_3 T_2	123 53	118.58	124 49	122 20
F_1 L_3 T_3	123.36	122.31	120 03	121.90
F_2 L_1 T_1	124 81	103.63	121.25	116 56
F_2 L_1 T_2	130.41	122.59	124 58	125 86
F_2 L_1 T_3	121.62	124 14	124.19	123.32
F_2 L_2 T_1	122.30	118 75	124.64	121.90
F_2 L_2 T_2	120.12	126 42	126.58	124.37
F_2 L_2 T_3	123.99	116 42	124.58	121 66
F_2 L_3 T_1	122.19	122.56	121.55	122.10
F_2 L_3 T_2	121.67	133.22	126.06	126.98
F_2 L_3 T_3	126.11	130.19	121 92	126.07
F_3 L_1 T_1	122 09	124.57	124 91	123.86
F_3 L_1 T_2	126 83	122 25	122 97	124 02
F_3 L_1 T_3	123.87	121.20	124.61	123 23
F_3 L_2 T_1	127 41	113.86	126.39	122 55
F_3 L_2 T_2	128 88	123 70	126.17	126.25
F_3 L_2 T_3	121.50	126.72	128 06	125.43
F_3 L_3 T_1	122.45	121.14	124.28	122.62
F_3 L_3 T_2	109 60	126.04	118.22	117.95
F_3 L_3 T_3	125.81	124.88	128.92	126.54

* F - Frequency (rpm) L - Dead Load (lbs) T - Time (sec)

F_1 = 1000 L_1 = 3000 T_1 = 20

F_2 = 1250 L_2 = 6000 T_2 = 40

F_3 = 1500 L_3 = 9000 T_3 = 60

The predicted densities calculated from this equation are given in Table C-2. A response surface was obtained by plotting these densities in three dimensions (see Fig. C-5). The purpose of this plot is to aid interpolation of the response between the points tested. The minimum density was obtained for the minimum time and minimum frequency tested—20 sec and 1,000 rpm, respectively. The response of density to increases in dead load was not sig-

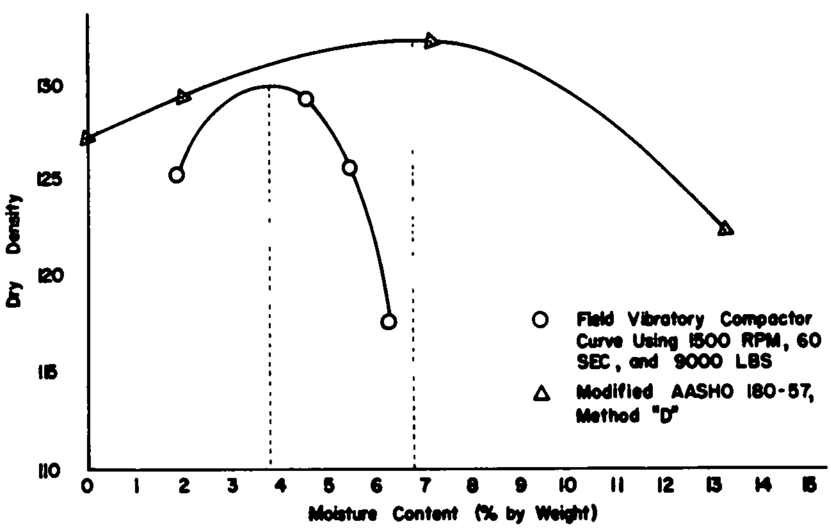


Figure C-4. Relationship between dry density and moisture content for vibratory and AASHO

TABLE C-2

DENSITIES PREDICTED BY EQ. C-2 FOR COMPACTION TESTS ON TYPE 2 CRUSHED STONE

Independent Variables		Dependent Variable	Independent Variables		Dependent Variable	Independent Variables		Dependent Variable
X_1	X_2	Y	X_1	X_2	Y	X_1	X_2	Y
10 0	20	119 04	10.0	40	120.16	10.0	60	120.86
10.5	20	119.13	10.5	40	121.96	10.5	60	121.54
11.0	20	119.29	11.0	40	123.43	11.0	60	122.17
11.5	20	119.52	11 5	40	124.54	11.5	60	122.73
12 0	20	119.82	12.0	40	125.31	12.0	60	123.24
12.5	20	120.18	12.5	40	125 75	12.5	60	123 68
13 0	20	120.61	13.0	40	125.83	13.0	60	124 08
13 5	20	121.11	13.5	40	125.57	13.5	60	124.41
14 0	20	121.68	14.0	40	124.97	14.0	60	124.69
14.5	20	122 31	14.5	40	124 02	14.5	60	124.91
15 0	20	123 02	15.0	40	122.73	15 0	60	125.07

Where X_1 is frequency in hundreds of RPM
X_2 is time in seconds
Y is Predicted Density, pcf

nificant in the range tested. The density attained a maximum of 125 83 pcf at 40 sec and 1,300 rpm. Further increases in time and frequency resulted in lower densities; hence, a peak in the response surface was obtained. Further examination of the plot past the peak density shows a rapid rate of increase in the density up to 125.07 pcf at 60 sec and 1,500 rpm. This increase rate, if extrapolated, implies that an increase in frequency and/or time would produce densities greater than the highest density obtained in this preliminary investigation.

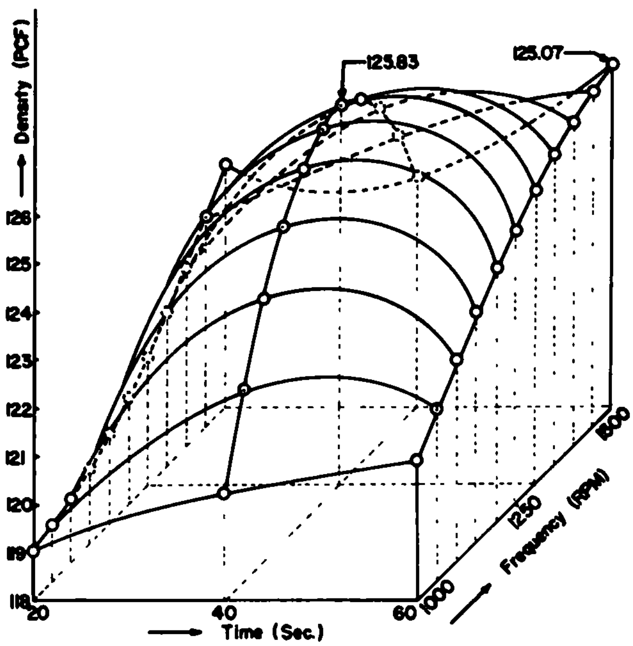


Figure C-5. Response surface for analysis of variance of compaction test data.

DETERMINATION OF PERCENT COMPACTION

The following conclusions were drawn from data obtained in this study. First, the magnitude of the surcharge need only be sufficient to maintain contact between the vibrator and the crushed stone. Second, the vibrator should be operated until no appreciable loss of surcharge occurs while the vibrator is in operation. Third, the density that can be produced by the vibratory apparatus depends on the lateral support of the material being compacted and thus on the initial density of the material. Because of this last conclusion a relationship was sought between the initial density or percent compaction and the change in density of the material after the operation of the vibrator.

To determine this relationship the test area was divided into four squares, each 8 ft by 8 ft. Each square was compacted to a different initial density as determined by averaging five or six volumeter measurements. The vibratory compactor was then operated in five or six locations on each test square. Care was taken to avoid areas where the volumeter had been used for the initial density measurement. After the vibratory compaction was completed, the volumeter was again used to determine the final densities in each test square. The entire process was repeated so that eight different initial densities, ranging from 112.9 pcf to 140.8 pcf, were investigated. The results of these tests are given in Table C-3.

A theoretical maximum density of 142 pcf was calculated using the Turner chart method (*215*), which is based on the gradation and specific gravity of the crushed stone. The initial density of each test section was then expressed as a percentage of the theoretical density and compared to the percentage change in density that resulted from vibratory compaction. The relationship between initial percent compaction and percent change in density is shown in Figure C-6. A coefficient of correlation of 0.96 and a standard error of 2.07 pcf were obtained for a linear regression analysis with the equation:

$$\rho_i = 97.28 + 1.796\Delta \qquad \text{(G-3)}$$

in which

ρ_i = initial percent compaction; and
Δ = percent change in density.

In one instance a negative change in density was recorded, indicating that the vibratory compaction device actually loosened the compacted stone. This occurred, however, with an initial compaction of nearly 100 percent and the reduction amounted to 1.4 percent. A change of 10 percent occurred for the lowest initial density used in this study.

A major problem in the operation of the vibratory compactor was its tendency to move laterally as well as vertically while in operation. This can be overcome by the use of a specially designed vibrator that has two counter-rotating weights to cancel all lateral forces and generate vertical forces only. An electrically operated vibrator would be more convenient than one that is air-driven.

SUMMARY

Although this method does not determine the "maximum" density of the material, it can be used to determine relative compaction by measuring the density of the crushed stone before and after it is vibrated. Thus, the necessity of obtaining a "maximum" density from laboratory or chart procedures is eliminated. This method does, however, require several in-place density tests for each determination. Although this method provides a relatively accurate but complex procedure to determine relative density or percent compaction, it does not appear to offer any appreciable advantages over existing methods. Consequently, a detailed field procedure using this technique has not been presented.

TABLE C-3

DATA FOR DETERMINATION OF RELATIVE COMPACTION OF TYPE 2 CRUSHED STONE [a]

DRY DENSITY (PCF)		AVG MOIST. CONTENT	INITIAL COMPACTION	CHANGE IN DENSITY
INITIAL	FINAL	(%)	(%)	(%)
127.6	131.0	3.3	89.9	2.6
121.9	128.5	4.9	85.9	5.4
140.8	138 8	5.2	99.1	−1.4
119.6	127.7	3.4	84.3	6.8
134.8	137.6	3.1	94.9	2.1
139 3	141.2	5.4	98.2	1.4
132.2	134.9	6.4	93.3	2.0
112.9	124.8	7.3	79.5	10.6

[a] Based on a maximum theoretical density of 142 0 pcf as determined by the Turner chart method (*215*)

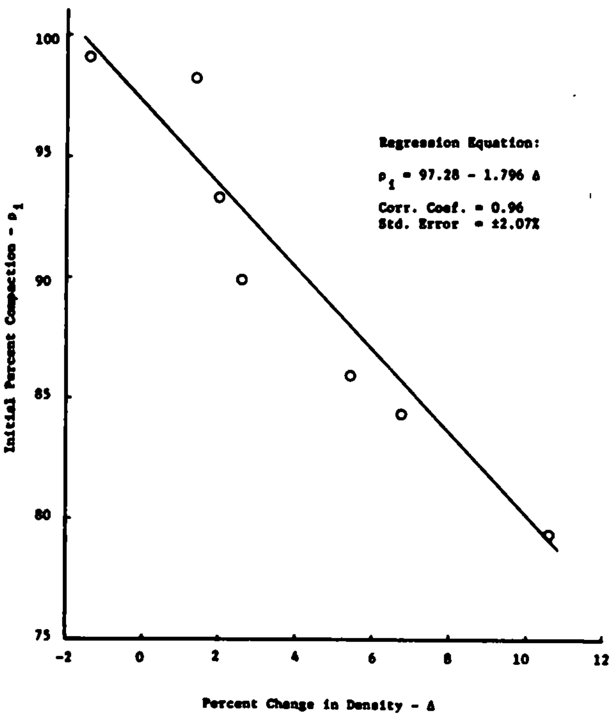


Figure C-6. Relationship between initial percent compaction and change in density for maximum density test procedure using Type 2 crushed stone.

APPENDIX D

POTENTIAL USES OF ELECTROMAGNETIC WAVES IN CONSTRUCTION CONTROL TESTING

With the impressive array of techniques that use certain regions of the electromagnetic spectrum in space probes and geophysical exploration, it is only natural that workers in the areas of materials testing speculate on the possibility that some of these techniques are applicable to their particular area of interest. In many cases these techniques have been successful. The phenomena of electromagnetic waves involved and the relationship of certain microscopic properties of materials to these phenomena over the entire electromagnetic spectrum were explored to discover new applications of their use in the field of construction control testing

ELECTROMAGNETIC WAVES

General Properties

The quantitative study of electromagnetic waves began with Sir Isaac Newton These studies were concerned with the most obvious source of electromagnetic waves, the visible region of the sun's spectrum. Some 200 years later, Hertz (*216*) generated the first wave in the electric power frequency range, thus validating Maxwell's theory which forms the basis of modern-day electromagnetic theory (*217*). During World War II, microwave and far infrared techniques were developed. These electromagnetic waves are of suitable character so as to bridge the apparent gap that existed between visible light and the radio or power frequency range. The spectrum has been extended on each end to include waves so short in length that they appear as discrete entities (photons) up to waves so long that they appear to have no periodic characteristic (as in direct current). The complete electromagnetic spectrum, as it is presently known, is shown in Figure D-1.

It should be noted that the divisions indicated in Figure D-1 represent approximate demarcation, because the regions actually diffuse, one into the other. Associated with the waves are vectorial quantities E and H, the electric and magnetic field vectors, respectively, of the waves. These vectors (shown in Fig. D-2) are perpendicular to each other and to the direction of propagation and are in phase unless disturbed by interaction with matter. A wave is monochromatic if only one wavelength is within the wave packet and is plane polarized if E lies in one plane only (say the xy) and H lies in one plane only (say the xz). In general, electromagnetics are neither monochromatic nor plane polarized, but these properties may be imparted to a wave if desired. The intensity of the wave is proportional to the square of E (or H).

Generation

Electromagnetic waves are generated by oscillations of charges within a substance. Cosmic or gamma rays, the shortest measured waves, are emitted by atomic nuclei, and their origin is least understood. X-rays are produced by motion of excited electrons in atoms, whereas visible light and ultraviolet radiation generally arise from periodic electron motion in molecules. Infrared or heat radiation arises from dipole radiation associated with molecular vibrations and/or rotations in the case of gases. Microwave frequencies arise from the rotational motion of some gaseous molecules and also can be generated by electronic tubes and semi-conductors. With suitable circuitry, waves ranging from 1 cycle/sec up to 10^{10} cycles/sec may be produced. The intensity, however, is not great at the extremely short or extremely long wavelength, as is shown in

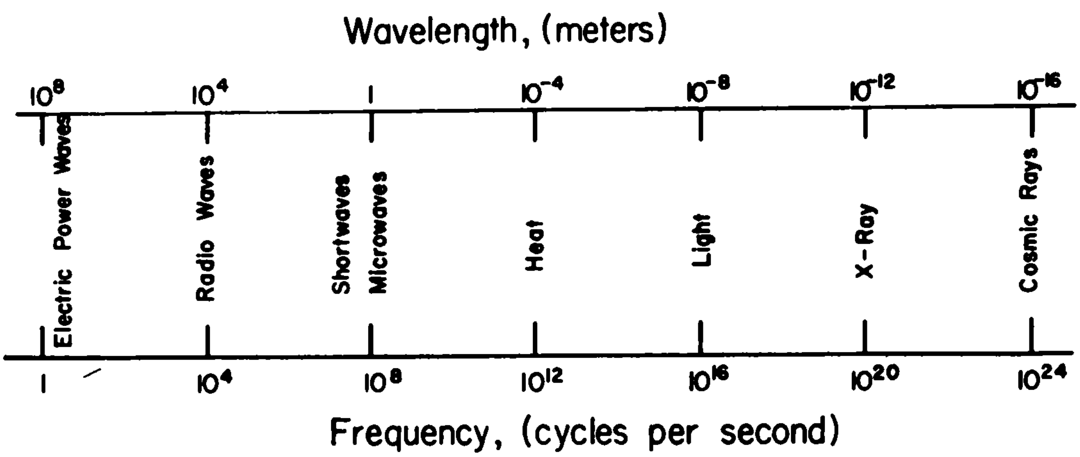


Figure D-1. The electromagnetic spectrum

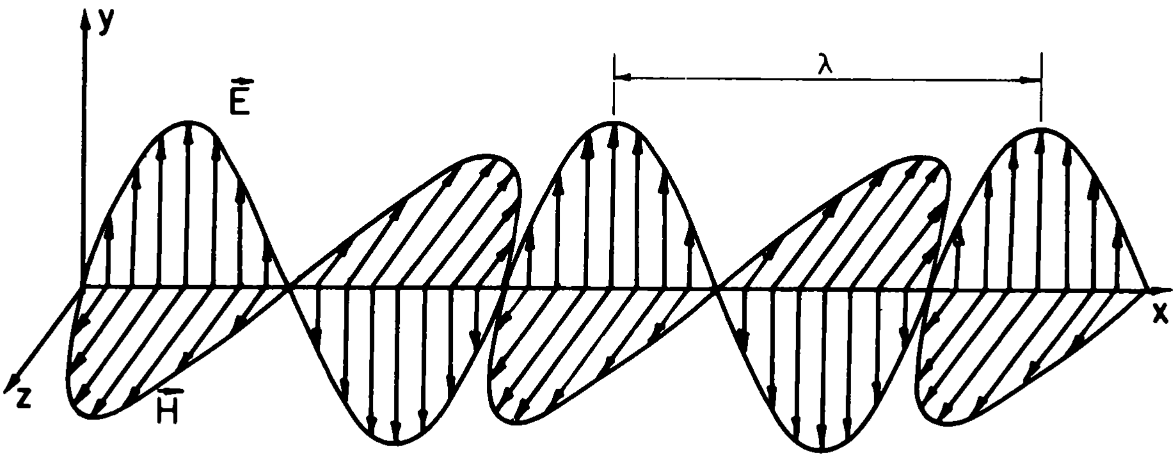


Figure D-2. The relationship between E, H, and direction of propagation of a traveling electromagnetic wave in the positive X-direction

Figure D-3 at two different temperatures of the hot body. This is the well-known black-body radiation cure (*218*), the explanation of which by Planck led to the formulation of quantum mechanics

Detection

The mode of detection of radiation depends severely on the region considered. The energy of short wavelength radiation (gamma rays and X-rays) is sufficient to produce ionization of gaseous atoms and can be detected by Geiger-Muller tubes as well as scintillation devices.

Visible, ultraviolet, and the near infrared radiation are measured by photoelectric tubes and photo cells. Infrared radiation of the intermediate wavelength range (10^{-6} m to 10^{-1} m) may be detected by thermocouples that convert radiant energy into electrical energy. At greater than 10^{-4} m wavelength the energy is quite small, and more indirect means are required for detection. This may be performed by use of crystal rectifiers as in radio circuits, although other more elaborate forms of intensity measurement and detection are available.

Interaction of Radiation with Matter

There are just three processes that may take place when an electromagnetic wave impinges on an object: the radiation is scattered, transmitted, or absorbed. Many other terms are used to describe the observed effects, but each term pertains to a special case of one of these three, especially scattering. For the purpose of simplicity, a wave is considered to be monochromatic, and the general case of non-monochromatic wave is handled by Fourier analysis. The object on which the radiation falls is considered to be a less free dielectric (i.e., a nonconductor) Before the three processes are described, some definitions (*219*) are required.

1. Total irradiation,* G—the total power incident to the surface of the system per unit area of irradiated surface.

2. Reflectance, ρ—that fraction of incident power that is reflected away from the surface (see Fig. D-4).

3. Absorptance, α—that fraction of the incident power absorbed by the object.

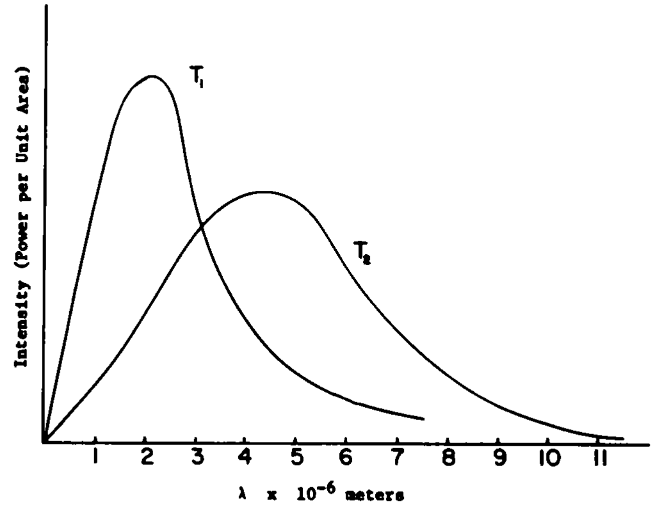


Figure D-3. Distribution of intensity of radiation versus wavelength at two different temperatures, $T_1 > T_2$.

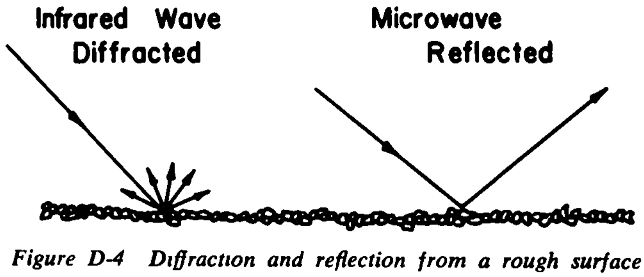


Figure D-4 Diffraction and reflection from a rough surface

* Irradiation is a more suitable quantity than intensity, the latter being incident power per solid angle per unit area of the source, projected normally to the detector

4. Transmittance, τ—that fraction of the incoming power transmitted through the system.

The energy balance requires:

$$G = \alpha G + \rho G + \tau G \qquad \text{(D-1a)}$$

or

$$\alpha + \rho + \tau = 1 \text{ for any system} \qquad \text{(D-1b)}$$

and

$$\alpha + \rho = 1 \text{ for an opaque system} \qquad \text{(D-1c)}$$

Even though these terms appear to have more kinship to the area of optics, their definitions are completely general and apply to any region of the spectrum. Note that a coefficient of scattering was not defined but, instead, a coefficient of reflection, ρ, was defined Actually, reflection is a special case of scattering, even though some literature sources provide no clear distinction. Specific reference to reflection is made as it perhaps is the most useful type of scattering as far as the present discussion is concerned.

Scattering

If an electromagnetic wave impinges on a dielectric, charges in the medium are set into periodic motion and radiate secondary waves from the surface. This phenomenon is scattering, and, by this definition, any of the processes of diffraction may be called scattering. A scattered wave is considered to be reflected when it can be identified as a ray of unidirectional propagation, and this occurs for surfaces that are optically smooth. Optically smooth infers that the average size of particles in the surface is less than one-fourth the wavelength of the incident wave. If the surface is not optically smooth the phenomenon of diffraction and interference results; i.e., the scattered ray is not identifiable except at certain locations. This is seen in Figure D-4, which shows a surface composed of an array of particles, each 1 cm in diameter.

In the case of infrared radiation of wavelength, say 10^{-4} m, the incident beam is diffracted and a diffraction pattern may be observed, whereas the microwave of length 1 m responds to the surface as though it were essentially smooth and the beam is reflected; thus, it represents a new coherent and unidirectional source of radiation.

Another example of the indiscriminate use of the words reflection, diffraction, scattering, etc., is in the area of X-ray spectroscopy. The interplanar distances in solids are such that an array of ions or atoms causes diffraction or interference patterns which may then be observed. These same X-rays falling on gases or vapors are scattered in a completely random fashion and the reradiation is totally incoherent.

There are no materials, or at least only a few, that will reflect X-rays and gamma rays by the stated definition, because their atomic dimensions are too large when compared with the wavelength. The diffracted radiation, except for X-rays or gamma rays, gives information primarily about the surface geometry and has limited utility for studies of the interior. The perfectly reflected radiation follows Snell's law, as does another phenomenon, that of refraction, which takes place as shown in Figure D-5. By requiring that the tangential components of the electric field of the wave be the same in medium 1 (air) as in medium 2 (the dielectric) one can derive Snell's law of reflection and refraction. For the reflected wave:

$$\phi_1 = \phi_1' \qquad \text{(D-2)}$$

and for the refracted wave,

$$\eta_1 \sin \phi_1 = \eta_2 \sin \phi_2 \qquad \text{(D-3)}$$

in which η_1 and η_2 are the indices of refraction of media 1 and 2, respectively.

The index of refraction is a fundamental characteristic of the material at hand and, although it is an "optical" term, it has a distinct counterpart for radio or power waves when they are incident on a dielectric. Refraction is not considered as scattering but is considered to be transmittance. The index of refraction of medium 2 may be a desired parameter in nondestructive testing and it can be determined by measuring properties of the *reflected* wave under special circumstances. This represents a considerable advantage over direct measurement of η_2 because one may have access only to the top surface of the dielectric. Consider the incident wave in Figure D-5 to be plane polarized with E either in the plane normal to the diagram, the N plane, or in a plane parallel to the diagram, the P plane. (The directions of both the incident and reflected waves are in the P plane.) In general, the reflected wave will have E components in both the N and P planes, but each component can be measured. By definition:

r_n = ratio of amplitude of reflected wave in N plane to amplitude of incident wave in N plane, and
r_p = ratio of amplitude of reflected wave in P plane to amplitude of incident wave in P plane.

It can be shown (*220*) that when the angle of incidence, ϕ_1, is close to zero, Fresnel's equations allow a simple relation betwen the values of r_n and r_p and the indices of refraction, namely:

$$r_p = r_n = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \qquad \text{(D-4)}$$

Measurements of r_p or r_n taken above the surface of medium 2 can be used for calculating η_2 if η_1 is known. These same relationships exist for any wavelength of radiation, but they may take on strange and unrecognizable appearances when the long wavelength region of the spectrum is considered

The discussion of reflection, refraction, transmission, etc , thus far has been in Maxwell field terms. These phenomena in the radio and power frequency range are best described by considering equivalent circuits. A traveling electromagnetic wave incident on a material, or a series of layered materials of different dielectric properties, is equivalent to the transmission of a current through a transmission line with different impedance values at points through the circuit. This equivalency is discussed by von Hippel (*221*).

Transmittance of Radiation

Transmittance is simply a measure of the radiation that passes through a material unaltered in frequency. A small portion of the reradiated wave normally associated with reflection may travel along the transmitted path, but this contribution is, in most cases, a negligible amount. The direction of the transmitted wave always changes due to refraction, as in Figure D-5, but the change may be so small as to go undetected when the indices of refraction are approximately equal. The velocity of the transmitted wave changes when passing from medium 1 into medium 2, the magnitude of which depends on the ratio η_1/η_2.

Absorption

The final alternative of an electromagnetic wave incident on a material is absorption, or, more appropriately, resonance absorption. Resonance absorption should be differentiated from the interaction that occurs when an incident wave produces oscillations of charges that are immediately reradiated as in scattering. The wave is annihilated in absorption but eventually may be reemitted. Absorption occurs when the frequency of the radiation is such as to excite electronic, atomic, molecular, and lattice oscillations that continually take place in the medium. These oscillations in an excited state are the same ones that cause radiation when the material is used as a source. If a frequency. ν, is absorbed it cannot be scattered or transmitted, and, conversely, the latter conditions preclude absorption A discrete absorption spectrum exists for gases, whereas for solids and liquids the discrete frequencies absorbed appear as wide absorption bands. These overlap and become continuous in the low-frequency range (10^{10} cycles/sec) due to an infinite number of lattice vibrational modes with extremely close frequencies. Eventually the material becomes transparent to some low-frequency radiation. The absorption spectrum characterizes a material to a large extent and the percent absorption relative to pure material is indicative of the amount of material present in a mixture. Absorption, the complement of transmission, forms the basis of absorption spectroscopy. The absorbed radiation is eventually converted to heat and the body will begin to reradiate, thus approaching a steady state. The most vivid example of this is the radiant energy from the sun, which strikes the earth's crust.

Mechanism of Radiation Interactions

The incident radiation can interact by scattering or by absorption. The manner in which charges are caused to oscillate and then reradiate as in scattering is explained by polarizability. This is simply a periodic distortion of natural space arrangements of charged particles (electrons, ions, etc.) by the electric field of the incident wave. If the frequency of the radiation is smaller than the natural frequency of particle motion, then the particles have no difficulty reacting to the periodic field. These forced oscillations, superimposed over the natural periodic motions that may be present, give rise to scattered radiation. There are four distinct ways in which an electric field can induce polarization; that is, there are four microscopic phenomenona that are slightly influenced by the periodic field (*222*). There are electronic motions, molecular and lattice vibrations, molecular rotations, and simple migration of charge carriers in nonhomogeneous materials. The polarizabilities are known as electronic polarizability, P_e; atomic polarizability, P_a; dipole orientation polarizability, P_d; and, space-charge polarizability, P_s. These are also listed in decreasing order of natural periodic motion so that, for example, a material may react to a field of 10^4 cycles/sec by the first three phenomena but the space charges react too slowly to be polarized. Thus, the dielectric constant or index of refraction, being a measure of polarizability of a material, is a function of the frequency of incident radiation. Only certain frequencies are absorbed by resonance and these frequencies are just those necessary to cause excitation of the periodic motion. Consequently, refractive index and absorption may be plotted as a function of frequency, as shown in Figure D-6, to show a very fundamental point of radiation interaction. Also shown are the relative contributions of each type of polarizability toward the refractive index, η, and it is seen that a material either scatters or transmits radiation, or both, until a resonance frequency is reached, at which point absorption occurs. Note also that in the gamma-ray region the incident radiation frequency is too high to interact via any of the mechanisms. Thus, this high-frequency radiation exhibits very little refraction or bending, because the refractive index is quite small in this region. These rays are scattered, however, by an alternate mechanism, as mentioned later.

Summary of Interaction

Other specific phenomena can occur when radiation falls on matter, but these are still special cases of the three main processes. Fluorescence and phosphorescence are each resonance absorptions and remission which is instantaneous in the former case and delayed in the later. Raman scattering is a process in which the scattered radiation has its frequency altered by certain amounts above and below the incident frequency. Compton scattering and the photoelec-

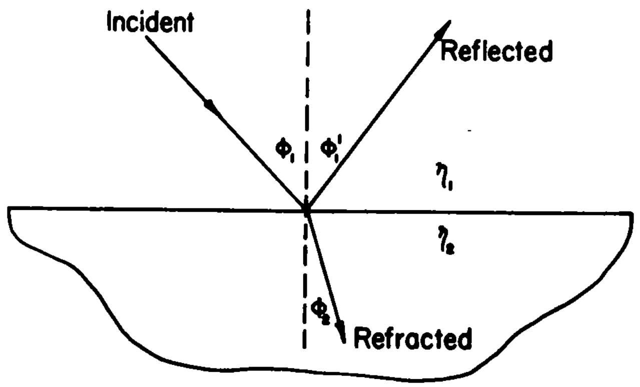


Figure D-5 Reflection and refraction of an incident beam at a dielectric interface, $\eta_1<\eta_2$.

tric effect are special nuclear-related processes when the incident radiation is of the gamma-ray range. Each of these processes can be usefully applied to the area of identification, and the last-mentioned effect, scattering of gamma rays, has been put to extensive use in nondestructive determination of soil density.

The absorption spectrum of a material is a virtual "fingerprint" of that material, and its usefulness as an analytical tool is obvious. The diffraction pattern of a solid when the incident radiation is of the X-ray range also can be used as an identification and also can give information concerning nonhomogeneity under certain circumstances. The refractive index also has been mentioned as a suitable parameter for measurement of material properties.

SPECTROSCOPY AS A TESTING TOOL

The term spectroscopy applies broadly to any study of material using electromagnetic radiation. In terms of the original types of interaction of radiation with matter, spectroscopy may consist of a study of scattering or absorption. These are classed as active forms of spectroscopy, in contrast to emission spectroscopy in which the material being studied is its own source of radiation In the active forms, the material under study is subjected to radiation and the resulting interaction is studied, whereas in the passive form of emission spectroscopy the radiation coming from the excited material is studied. No information is gained from emission spectra that cannot be obtained from absorption spectra. Experimental techniques and the accessibility of the sample generally dictate the choice. In this section the various forms of spectroscopy are discussed, beginning at the high-energy gamma rays and progressing to the low-energy radio waves. The areas in which spectroscopy has been beneficial to nondestructive testing and how it may or may not be useful for construction control of highway materials are presented in the following discussion

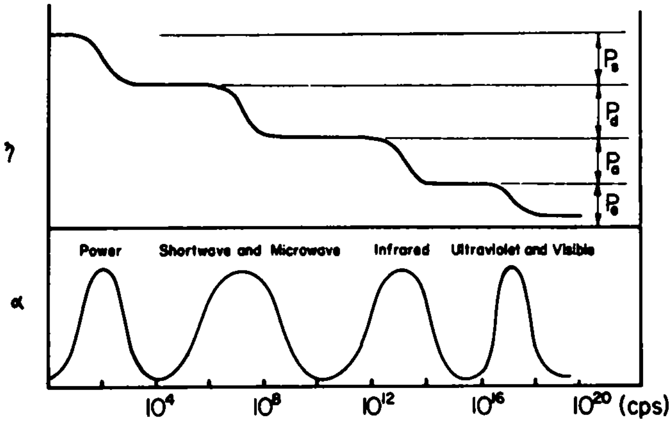


Figure D-6 Dielectric constant, γ, and absorption, α, versus frequency, ν

Gamma-Ray Spectroscopy

The absorption or emission of gamma rays can be used for identification of elements present but, because of health safety problems and the availability of other cheaper means, this aspect of gamma-ray spectroscopy for quality control of construction is useless Of much greater value is the scattering of gamma rays by nuclei. The scattering of these waves by randomly oriented nuclei (random because the wavelength is so small) is similar to the incoherent scattering of X-rays by gaseous atoms. The scattering is proportional to the number of scattering objects per unit volume and the inherent radiation is attenuated after traveling through several unit paths A unit path is the thickness of a material necessary to reduce the intensity by a factor of $1/e$. Thus, the intensity of a signal reaching a detector is diminished, depending on the density of the material through which the gamma rays pass. The intensity of the signal reaching the detector also depends on the chemical composition of the material, but this problem can be circumvented by use of the air-gap procedure (*223*). Thus, a nuclear gauge, employing scattering, is a common means of nondestructive density determination. One major aspect of gamma rays that is practically nonexistent in the lower-energy region of the spectrum is that these waves have higher penetrating power Gamma rays have high penetrating power even for visibly opaque materials, so that the measured attenuation can be indicative of properties of the interior of the material. The high penetrating power comes from the fact that gamma rays must collide with the nucleus of an atom to be scattered The high-energy waves simply pass through the "soft" electron cloud surrounding the nucleus. Another use of this high penetrating power is in the area of gamma-ray radiography (*224*). Air voids and inclusions in metal objects show up vividly as spots of less attenuation on a detector screen behind the specimen.

X-Ray Spectroscopy

X-rays have the ability to penetrate the outer valence electrons of atoms, but are stopped by the inner core of electrons This inner core is several orders of magnitude larger than nuclei so that the penetrating power of X-rays is less than that of gamma rays. The power is still significant, however, and X-rays are able to pass through human tissue and most organic materials. As an identification tool, X-ray spectroscopy is relatively safe and has been put to extensive use Generally, the interference or diffraction pattern of X-rays scattered from the layers of ions or atoms in a solid is observed. The scattered radiation pattern follows Bragg's law and the structure of solids can be obtained very accurately. X-ray scattering may be used as a measure of density if the material is not too thick and contains mainly organic material. The use of X-rays for density determinations or inorganic materials 2 to 3 in. thick is not feasible. Inclusions, porosity, fatigue points, etc., in a film or sheet of material are readily observed by X-ray radiography.

Ultraviolet, Visible, and Infrared Spectroscopy

Spectroscopic studies in the ultraviolet, visible, and infrared regions are lumped together because all of these have much in common both experimentally and theoretically. Spectroscopy in the ultraviolet to infrared region is either absorptive or emissive, each giving the same information. Absorption spectroscopy is widely used; the experimental setup is shown schematically in Figure D-7. A source emits polychromatic radiation of many frequencies, three of which are shown in expanded scale. This beam impinges on the sample, usually perpendicularly so as to minimize loss by reflection, and resonant frequencies are absorbed. These may be instantaneously reemitted, but the reemitted waves are randomly directed so that only a very small portion travels in the direction of the transmitted frequencies. In Figure D-7, ν_2 is absorbed and ν_1 and ν_3 are transmitted. The emerging beam is still polychromatic and is dispersed into its separate components by a dispersing element, generally a prism of suitable refractive index. Actually, all transmitted frequencies are superimposed on each other and impinge on the prism at the same location. The various frequencies are dispersed so that, as the prism rotates, the transmitted radiation passing through the slit is essentially, but not totally, monochromatic. A detector, measuring intensity, notes the absence of energy when the prism is oriented in such a way that ν_2 should be passing through the slit. A plot of intensity of radiation reaching the detector (or the absence of radiation) versus angle of rotation of the prism can be made. Each setting of the prism corresponds to a given frequency, and a plot of either percent absorption or percent transmission versus frequency or wavelength can be performed automatically by a servo-recorder. Owing to the limitations of the system the absorption bands for which the centers correspond to the resonance frequencies are broadened.

An emission spectrum is obtained in a similar fashion, except that no source is present. Instead, the sample is excited by heat or a spark and is caused to emit characteristic radiation; i.e., just those frequencies that are absorbed in absorption spectroscopy. This is the principle of flame photometry.

The spectrum in the ultraviolet and visible range is indicative of the elements present (atomic absorption spectroscopy), whereas the spectrum in the lower visible and infrared is indicative of chemical bonds present (electronic and vibrational spectroscopy) Each absorption band corresponds to some type of transition of a microscopic system from a state of lower energy to one of higher energy and the exact frequency necessary to produce this transition is quite sensitive to chemical composition. No two compounds have the same spectrum. However, it cannot be stated absolutely that the intensity of an absorption or emission band is proportional to the amount of material present This is true only if the same absorption band is compared in the same compound at different concentrations of material. Absolute intensities depend on other phenomena explained by quantum mechanics; and a certain absorption band in a material of 10 percent concentration

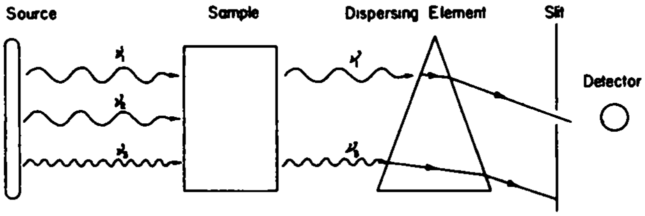


Figure D-7. The essential elements of an absorption spectrometer.

may be stronger in intensity than another band in another material at 50 percent concentration.

Absorption spectroscopy as a form of acceptance testing has wide use in the highway construction industry. Tests for adulteration of paints and coating, aging of liquids used in mixtures, and related tests are performed quickly and accurately. However, when an attempt is made to apply absorption spectroscopy to the problem of quality control one major difficulty is apparent. It is simply that the sample must transmit some radiation in order to detect the unabsorbed radiation, and a detector must be placed behind the sample. These requirements limit absorption studies to thin samples under laboratory conditions. Emission spectroscopy may appear promising because no source is required—only an excited sample. The emission spectrum, however, will originate from the first few microns of surface molecules and cannot be representative of interior composition, as is the case in absorption spectroscopy. If the surface is assumed to be representative of the entire material, then emission spectroscopy may be used to determine moisture content, water of hydration, and chemical composition. The error inherent in this assumption is obvious, although some attempts have been made on terrain analysis by reflection studies (*225*). Infrared sensing devices are capable of scanning a terrain so as to detect submerged bodies (such as peat bogs) that emit radiation at a rate different from surrounding material. Strictly speaking, this is not a form of spectroscopy.

Other Forms of Spectroscopy

The waves below the infrared portion of the spectrum are of low energy and usually are reflected. A slight portion of the emission spectrum may be superimposed over the reflected radiation, but still this can give information concerning the surface only.

Another form of spectroscopy using the radio frequency range is nuclear magnetic resonance spectroscopy (NMR). Here, a sample is placed in a static magnetic field which perturbs some microscopic phenomenon.

Summary of Spectroscopy

Spectroscopy as a testing device for quality control, especially for solid-state aggregates, is limited almost exclusively to gamma-ray and X-ray scattering. The other forms are suitable for acceptance testing but have no future for determination of bulk properties, except perhaps for the special case of perfect crystals, which are not likely to be found in road construction materials.

OTHER POSSIBLE USES OF ELECTROMAGNETIC WAVES

Refractive Index Measurement

It has been mentioned that the refractive index of a material is a monotonic function of density for a given chemical composition. If one uses polarized radiation of the 1-m-wavelength region so that no diffraction results, it should be possible to measure the refractive index of the homogeneous material, as discussed previously. A calibration curve of density versus refractive index can be constructed which should hold for any substance of the same chemical composition. Thus, the density of certain foam plastics (such as styrofoam) and some synthetic ceramic materials could be obtained. For perfectly dry aggregates the same information might be obtainable; however, small variable amounts of water, with its high dielectric constant, will produce large variations in the refractive index, hiding small variations due to density of the inorganic aggregate.

Thermal Radiation Testing for Flaws

Infrared radiation may be used solely as a means of temperature determination. A material is heated uniformly on one side by a heat source which moves over the sample. After a short time, the total radiation emitted by the specimen at a given location on the other side is measured. The amount of radiation is proportional to the temperature so that essentially the rate of heat flow through a material is measured. A flaw or air void in the interior represents a blockage of heat flow and the surface immediately over the flaw is cooler. These techniques have been studied and are found to be applicable for studies of laminations, bonding, welded joints, etc. (*226*).

When one attempts to apply these techniques to testing of road construction materials, it becomes obvious that alterations are necessary. First, the emitted radiation must be measured from the same side as the heat source. With thick materials and infinite planar dimensions, a powerful heat source is required which makes detection difficult. In the case of a fresh asphalt layer, the heat is already present and the measurement of surface temperatures at various locations may be considered as indicative of interior conditions. For example, locations of excess asphalt or excess aggregate may cause surface temperatures to be different from those of a "normal mix" or acceptable specimen. The pavement loses heat by conduction to the subgrade and by convection and radiation from the top surface. A knowledge of the subgrade temperature seems necessary, and this alone makes the procedure time-consuming.

CONCLUSIONS

Use of electromagnetic waves as tools in the area of nondestructive testing is at present restricted mostly to acceptance testing. These involve the many branches of spectroscopy and are carried out under laboratory conditions on small, specially prepared samples. Quality control testing (i.e , in-place testing of materials under field conditions) by use of electromagnetic waves is restricted almost solely to scattering of gamma rays or X-rays. This is necessarily so because to gain knowledge of the interior requires considerable penetration by the radiation. The best-known examples are uses of gamma-ray scattering and neutron bombardment for density, moisture content, and asphalt content (*227, 15*).

The main obstacle restricting extensive use of other regions of the spectrum must surely be the fact that phenomena arising in these other regions are surface effects and cannot give reliable information about the interior. This must be interpreted in terms of the primary objectives of field-testing of highway construction (i.e., the determination of bulk and composite properties of soil, aggregate, and cementing materials).

APPENDIX E

ANNOTATED BIBLIOGRAPHY OF RAPID TEST METHODS

ASPHALTIC PAVING MIXTURES

Asphalt Content

1. BRAKLEY, B. A., "A Vacuum Extractor for Bituminous Mixtures." A paper presented at ASTM 68th Ann. Meeting, Lafayette, Ind (June 1965).

   Describes a procedure for the rapid field determination of the asphalt content of hot asphaltic mixtures Asphalt is extracted from sample by using methylene chloride and vacuum filtering.

2. HOLLAND, L. E., "Asphalt Content of Bituminous Mixtures." A paper presented at ASTM 67th Ann. Meeting, Chicago (June 1964).

   Describes a procedure for the rapid field de-

termination of the asphalt content of asphaltic mixtures. A Chapman-type flask is used to determine the displacement volume in kerosene of the aggregate blend and also the asphaltic mixture. These volumes, in conjunction with a set of curves, permit determination of the asphalt content.

3. HUGHES, C. S., "Density and Asphaltic Content of Bituminous Pavements." A report given for HRB Special Committee No 8 (Sept. 28-29, 1964).

   Discusses briefly the development and application of nuclear devices for the determination of asphalt content and density of bituminous pavements.

4. LAMB, D. R., and ZOLLER, J. H, "Determination of Asphalt Content of Bituminous Mixtures by Means of Radioactive Isotopes." *Proc HRB*, Vol. 35 (1956) pp. 322-326.

   Discusses briefly the principles involved and the test procedure developed by the authors to determine the asphalt content of bituminous mixtures by means of radioactive isotopes. From data accumulated a curve of counts of slow neutrons versus asphalt content is presented for the samples tested. It is concluded that a rapid and reasonably accurate technique for determining asphalt content by means of radioactive isotopes has been found.

5. LEE, A. R., GOUGH, C. M., and GREEN, E. H., "A Rapid Method of Analysis for Bituminous Materials." *Roads and Road Const* (London), Vol. 29, No. 341, pp. 128-130 (May 1951)

   A rapid test method for analyzing a sample of bituminous road mixture is described. Procedures using methylene chloride as the solvent give fast determinations of binder content. A modification of the test method enables the determination of the grading of the aggregate at the same time the binder content is determined.

6. RICHARDSON, C, *The Modern Asphalt Pavement* 2nd ed., John Wiley, pp 351, 514 (1908).

   Describes a procedure for a stain test that is applicable to hot sheet asphalt mixtures.

7. SMITH, W. F., "The Supplementing of Laboratory Control of Hot Mix Plants by Simple Manual Tests." *Proc. Assn. of Asphalt Paving Technologists*, Vol 24, pp. 392-398 (1955).

   Describes a procedure for a stain test that can be applied to fine-graded asphaltic concrete.

8. TAYLOR, F. G, and TATTERSALL, E., "The Road Research Laboratory Machine for Rapid Analysis of Bituminous Road Materials." *Roads and Road Const.* (London), pp. 131-132 (May 1951).

   Describes the mechanical details of the apparatus used in the rapid methylene chloride method for the simultaneous determination of aggregate gradation and binder content.

9. WALTERS, H. W., "Nuclear Asphalt Content Determination at the Job Site." *Hwy. Res. Record No. 117* (1966) pp. 54-70.

   Describes a procedure developed that permits rapid determination of asphalt content by a nuclear method. Asphalt contents determined by the nuclear method are correlated with reflux extractor tests and plant checks.

Stability

10. CHU, T. Y., and SPANGLER, M. G., "Plant Stability Test for Hot-Mix Asphaltic Concrete Mixtures." *Roads and Streets*, pp. 83-92 (Oct. 1950).

    A new rapid method of testing for the control of asphaltic concrete mixtures at hot-mix plants is suggested. A single mold has been developed for both molding and testing. Specimen is tested in compression when the mixture cools slightly to a prescribed temperature.

Bulk Density

11. HUGHES, C. S., "Investigation of a Nuclear Device for Determining the Density of Bituminous Concrete." *Proc. Assn of Asphalt Paving Technologists*, Vol 31, pp. 400-417 (1962).

    Reports on a laboratory investigation undertaken to evaluate a commercially available nuclear density gauge. Conclusions were: (1) the probe is precise; (2) the theory of a linear relationship between density and count rate seems to hold; (3) temperature and moisture do not affect results as much as aggregate type and surface texture.

12. HUGHES, C. S., and RALSTON, H. H., "Field Testing of a Nuclear Density Device on Bituminous Concrete." *Proc. Assn. of Asphalt Paving Technologists*, Vol. 32, pp. 106-147 (1963).

    Reports on a field study of a commercially produced nuclear density gauge. Conclusions were: (1) a single calibration curve cannot be used for all projects, (2) different aggregates require different calibration curves; however, the use of a single aggregate does not ensure that only a single curve can be used; (3) effect of surface texture is more pronounced for base courses; (4) each lift should be tested as it is laid; (5) nuclear densities appear to be more than twice as variable as conventional densities, but speed of testing helps to compensate for this decrease in accuracy.

13. Sloane, R. L., "Development of a Nuclear Surface Density Gauge for Asphaltic Pavements." *HRB Bull. 360* (1962) pp. 1-17.

Describes the development of a nuclear method of determining asphalt pavement density in place, using a surface density gauge.

See also annotated Ref. No. 3.

Void Content

14. Ekse, M., and Zia, Z. T., "Field Measurement of Air-Permeability for Control of Bituminous Mat Construction." *Proc. Assn of Asphalt Paving Technologists*, Vol. 22, pp. 44-55 (1953).

Describes the development and application of an apparatus for measuring the air-permeability of specimens removed from bituminous pavements.

15. Ellis, W. H., and Schmidt, R. J., "A Method for Measuring the Air Permeabilities of Asphalt Concrete Pavements." *STP No. 294*, ASTM, pp. 85-91 (1960).

Describes the development of a method of measuring the air-permeability of bituminous pavements The equipment developed is portable and permits a rapid determination of permeability by measuring the actual volume of air coming through the pavement in a given time under a uniform differential pressure.

16. Hein, T. C., and Schmidt, R. J., "Air Permeability of Asphalt Concrete." *STP No. 309*, ASTM, pp. 49-62 (1961).

Discusses the importance of permeability in bituminous pavements and describes equipment and a procedure for measuring air-permeability in the field on asphaltic concrete while still hot.

17. Kari, W. J, and Santucci, L. E., "Control of Asphalt Concrete Construction by the Air Permeability Test." *Proc. Assn of Asphalt Paving Technologists*, Vol. 32, pp. 148-170 (1963).

Field data are presented using an air-permeability apparatus during and immediately after construction. The relation between in-place measurements and the relative Marshall density of cores is established for two specification mixes. Pavement permeability is shown to be affected by paver speed and amount of rolling; pavement variability presumed to be due to mix segregation in the paver is demonstrated

18. Soiltest, Inc., *Operations Manual. Asphalt Paving Meter*. (1963).

Presents background information on the use of an air-permeability device and describes the recommended procedure when using the Asphalt Paving Meter.

19. Pyk, N. C., Hathaway, C. W., and Warnick, C. C., "Development of an Asphalt Pavement Air Permeameter and Evaluation of Its Use." *Res. Report 2*, Eng. Experiment Station, Univ. of Idaho (Sept. 1965).

Describes the development and field evaluation of an air-permeability device known as the Idaho Pavement Permeameter.

20. Zube, E., "Permeability Test." *Calif. Highways and Pub. Works*, pp. 53-63 (July-Aug 1963).

A water permeability device used by the California Division of Highways is described and its use in evaluating the compaction of bituminous pavements is documented.

BASE COURSE CONSTRUCTION AND SOIL COMPACTION

Moisture Content

21. Balla, A., "Rapid Soil-Moisture Determination in the Field, Without Sampling." *Agrartudomany*, Vol. 3, pp. 430-435 (1951).

A rapid technique for determining soil moisture by dielectric capacity is described. The apparatus consists of a high-frequency dielectric measuring unit and a condenser shaped so as to facilitate its insertion into the soil.

22. Bloodworth, M. E., and Page, J. B., "Use of Thermistors for the Measurement of Soil Moisture and Temperature." *Proc. Soil Science Soc. of America*, Vol. 21, No. 1, pp. 11-15 (Jan.-Feb. 1957).

It has been recognized that the thermal method of soil moisture measurement offers some of the best possibilities of being unaffected by salt, in addition to covering the available moisture range with acceptable sensitivity. Laboratory experiments indicate that this method of moisture measurement covers the available moisture range, with greatest sensitivity near and below field capacity.

23. Blystone, J. R., Pelzner, A, and Steffens, G. P., "Moisture Content Determination by the Calcium Carbide Gas Pressure Method." *Pub. Roads*, Vol 31, No. 8, pp. 177-181 (June 1961).

A moisture testing instrument, called the Speedy moisture tester, is described. The recommended procedure for its use in rapid determination of soil moisture is given. Possible applications at site locations and field laboratories are listed.

24. Bouyoucos, G, "Measuring Soil Moisture Tension." *Agric. Eng.*, Vol. 41, No. 1, pp. 40-41 (Jan. 1960).

Presents a new calibration on the plaster-of-paris electrical-resistance block method for measuring soil moisture under field conditions, based on the moisture tension in soils.

25. Croney, D., Coleman, J. D., and Currer, E. W. H., "The Electrical Resistance Method of Measuring Soil Moisture." *Brit. J. of Applied Physics* (London), Vol 2, pp. 85-91 (Apr. 1951).

Analyzes the electrical resistance method of measuring soil moisture and shows that although it can be used to determine soil suction with reasonable accuracy, its application to measurement of soil moisture content is limited. Relationships were determined between moisture content by suction plate, centrifuge, and vacuum-dessicator methods. Relationships were developed between resistance of gauge and moisture content of absorbent gauges and the accuracies of the different ranges of suction were established.

26. Croney, D, and Jacobs, J. C., "The Rapid Measurement of Soil Moisture Content in the Field." *Roads and Road Const.* (London), Vol. 29, No. 353, pp. 191-194 (July 1951).

Defines a standard determination of moisture content and states that an acceptable accuracy is within one-tenth of the true value, and an acceptable time requirement needs to be about 5 to 10 min. The alcohol drying method, the alcohol extraction method, and the pycnometer method are analyzed and evaluated in terms of the requirements. A Speedy moisture tester is described.

27. de Plater, C. V, "A Portable Capacitance-Type Soil Moisture Meter." *Soil Science,* Vol. 80, No. 5, pp. 391-395 (Nov. 1955)

Briefly describes an improved and portable capacitance meter suitable for field or laboratory investigations. A measure of soil moisture can be obtained within ½ min after inserting the probe into the soil. The meter also may be used with plaster blocks.

28. Hancock, C. K., and Hudgins, C. M., Jr, "Determination of Water in Soils by an Indirect Conductivity Method." *Analytical Chem.,* Vol. 26, No. 11, pp 1738-1740 (Nov. 1954).

Simple, rapid methods are needed for the determination of water in materials that may contain electrolytes. Using methyl and ethyl alcohols, studies of systems of alcohol, acetone, water, and sodium chloride show that conductivity is nearly linear with the water content over the range of 0 to 10 percent of water. The procedure requires 10 min. Encouraging results have been obtained in the determination of water in soils.

29. Houlnick, C., "Water Content of Sands." (In French), *Annales des Ponts et Chaussées* (Paris), Vol. 121, No. 6, pp. 176-177 (1951).

A rapid method of determining the water content of sand consists of exposing a 100-gm sample in a shallow dish to infrared radiation from a lamp. The sample is kept stirred during the drying period (about 30 min). The method is more rapid than oven treatment, and permits the use of a relatively large sample.

30. U.S. Department of Commerce, *Hydraulic Proctor Needle.* Soils Branch, Div. of Phys. Research, BPR (May 1958).

A new hydraulic Proctor needle is presented and described. Its advantages are: (1) better control of rate of penetration; (2) more accurate reading at the "break point"; and (3) better duplication of results.

31. Ivanov, P. V., "A Rapid Method of Determining Soil Moisture." (In Russian), *Pochvovedenie* (Russia), Vol. 3, pp. 61-65 (1953).

Describes a rapid, simple method in which the soil is dried by a flame of burning alcohol which is suspended above it. The method can be used in the field and the procedure enables rapid testing.

32 Texas A&M University, "Indirect Conductivity Method Reveals Soil Moisture Content in Brief Time." *Texas Eng. Experiment Station News,* Vol. 8, No. 1, pp. 15-16 (Mar. 1957).

The indirect conductivity method for determining moisture content most recently proved itself with soils. It has been successfully applied also in moisture determinations involving cooked cottonseed meats and cottonseed meal. The method involves agitation of a sample with salt and ethyl alcohol-acetone mixture and measurement of the conductivity of the resulting supernate.

33. Johnson, A. I., "Methods of Measuring Soil Moisture in the Field." *Water Supply Paper 1619-U,* Geol. Survey, U.S. Dept. of Interior, pp. 1-25 (1962).

Much equipment and many methods have been developed to measure soil moisture under field conditions. This report discusses and evaluates the various methods for measurement of soil moisture and describes the equipment needed for each method. The advantages and disadvantages of each method are discussed and an extensive list of references is provided.

34. Johnston, W. R., and Perrier, E. R., "Use of Direct and Alternating Current Meters for Measuring Resistance of Soil Moisture Units." *Soil Science,* Vol. 91, No. 6, pp. 360-363 (June 1961).

An experiment was conducted to compare the use of a c. and d.c. meters in determining resistances of electrical resistance units for measuring soil moisture in situ. The comparison was made on each of six commercially available units installed in field soil. The results indicate that the electrical resistance of soil-moisture measuring units may be determined by means of d.c. meters, provided care is taken to minimize the effects of electrolysis and polarization.

35. KIRKHAM, R. H. H., "A Buoyancy Meter for Rapidly Estimating the Moisture Content of Concrete Aggregates." *Civil Eng. and Pub. Works Review* (London), Vol. 50, No. 591, pp. 979-980 (Sept. 1955).

To obtain concrete of uniform strength a buoyancy moisture meter has been developed which, after calibration for the particular aggregate, enables the determinations to be carried out accurately and rapidly by semi-skilled labor. A single determination takes about 4 min.

36. MCINTOSH, J. D., "The Siphon-Can Test for Measuring the Moisture Content of Aggregates" *Res. Note Report 6*, Cement and Concrete Assn. (London), (1951).

The siphon can is a watertight container with two siphon tubes in the cylindrical section between upper and lower conical portions. The volume of water displaced by a known weight of moist aggregate is determined by siphoning into a measuring cylinder. A special transparent scale fitted to the cylinder permits direct reading of moisture content by weight

37. TEXAS A&M UNIVERSITY, "New Soil Moisture Test." *Texas Eng Experiment Station News*, Vol. 1, No. 1 (Mar. 1950).

The alcohol soil moisture test is offered as an improvement over methods currently used Only 10 min are required; accuracy is within the established criterion and calculations are at a minimum. Equipment is easily transported; 40 to 50 tests may be performed with 1 gal of alcohol.

38. PERRIER, E. R., and EVANS, D. D., "Soil Moisture Evaluation by Tensiometers." *Proc Soil Science Soc. of America*, Vol 25, No 3, pp. 173-175 (May-June 1961).

Four different types of tensiometers were compared and found to be similar within their range of measurement based on moisture desorption curves. Only a slight difference in range was found between the instruments.

39. ROWLAND, E. F., FAGAN, T. D., and CRABB, G. A., JR, "A Slide Rule for Soil Moisture Determination." *Agric. Eng*, Vol. 35, No. 3, pp. 163-164 (Mar. 1954).

A point of difficulty in the use of the electrical-resistance method of soil-moisture determination is the precise correction of observed resistances of moisture blocks to compensate for soil temperature. The slide-rule method developed by the authors simplifies this correction to a single manipulation of the slide rule.

40. SANDOVER, J. A, "Electrical Determination of the Moisture in Sand." *Proc. ASCE, J. Construction Div.*, Vol. 88, No. CO2, pp. 25-39 (Sept. 1962).

The electrical gauge described registers immediately the moisture content of sand or any similar inert granular material by means of the conductivity of the water. A number of sand samples have been tested and the results are presented graphically.

41. STEFFENS, G. P., and RING, G. W., "Advances in Methods for Field Testing of Densities and Moisture Content of Earthwork, Base, and Surface Courses." A paper presented at AASHO 46th Ann. Meeting, Detroit (Dec 1960).

Presents a summary of all factors involved in controlling compaction on field projects, including a review of several types of equipment used. Summarizes nuclear methods of measuring moisture and density and reviews data obtained by the Bureau of Public Roads

42. THOMAS, W. F., "Moisture Determination in Soils and Stabilized Soils." *Roads and Road Const.* (London), Vol. 36, No. 425, pp. 140-147 (May 1958).

An attempt has been made to determine the moisture contents of a variety of soils, before and after stabilization, over a wide range of moisture contents Two well-known chemical methods (alcohol extraction and entrainment distillation) have been modified for use with soils, and two new methods have been introduced: (1) the first estimates moisture by the change in the refractive index of dioxane on the addition of water; (2) the second is an adaptation of the calcium carbide pressure technique.

43. WILDE, S A., and SPYRIDAKIA, D. M., "Determination of Soil Moisture by Immersion Method." *Soil Science*, Vol. 94, No. 2, pp. 132-133 (Aug. 1962)

The difficulties of the gravimetric method were overcome by Maiboroda who suggested use of the immersion method. This rapid field procedure is based on the fact that an absolutely dry weight of a moist soil can be obtained by weighing the soil in water. The immersion method proved to be of special value in calibration of the neutron-scattering probe.

44. VAN DER MAREL, H. W., "Rapid Determination of Soil Water by Dielectric Measurement of Dioxane

Extract." *Soil Science,* Vol. 87, No. 2, pp. 105-119 (Feb. 1959).

The decametric dioxane extraction method to determine soil water of air-dry soils and of soils wetted beforehand to a maximum of about 50 percent H_2O is compared with oven-drying method Details are given about the analytical procedure. The theoretical side of the method also is discussed to some extent.

Density

45. BRAND, L., "A Study of the Sand Cone and Rainhart Volumeter Methods of Measuring the Volume of Density Test Holes." *Research Report,* Va. Council of Highway Invest. and Research, Charlottesville (Nov. 1961)

Discusses the precision and relative accuracy of two of the most widely used methods of measuring test hole volumes—the sand method (with two variations) and the Rainhart water-balloon volumeter method.

46. COFFMAN, B. S., "Controlling Accuracy with More Rapid Sand Cone Density Test." *ASTM Bull. No. 218,* pp. 57-59 (Dec. 1956).

The in-place density test using sand-cone apparatus with base plate assumes a level soil surface and that the plane of the bottom of the plate and the plane of the soil surface are conjugate or continuous. Leveling the soil surface requires care and is time-consuming. The alternative two-test procedure is accurate but requires twice as much time and more equipment.

47. DAVIDSON, D. T., and HANDY, R. L., "Rubber-Balloon Apparatus for Measuring Densities of Soils in Place " *HRB Bull. 122* (1956) pp. 13-22.

There is a need for an apparatus which could be used either on level, sloping, or vertical faces. The apparatus needs to be rugged and compact. A new rubber-balloon apparatus was developed and is described. Test data are presented.

48. MINOR, C. E., and HUMPHRES, H. W., "A New Method for Measuring In-Place Density of Soils and Granular Materials." *HRB Bull. 93* (1954) pp. 49-50.

The Washington Densometer has been developed to overcome error and time factor of conventional methods. The instrument uses a fluid-filled balloon to measure the volume of the hole. A cylinder and piston activate inflation and deflation of the balloon.

49. "New Road Test Device Described." *Colorado Info.,* Colo. Good Roads Assn., Vol. 18, No. 12, p. 6 (Mar 22, 1956).

A new device, called the "Haynes bomb," for saving time and carefully calibrated sand in making density field tests during road construction is reported. The "bomb" saves from 40 to 70 percent of test sand used in the old method of determining volume of a test hole. The constant, known volume vessel is placed into the hole and sand is then poured around it.

50. REDUS, J. F., "A Study of In-Place Density Determination for Base Courses and Soils." *HRB Bull. 159* (1957) pp. 24-40

Four methods of measuring in-place density to determine amount of error were studied: sand displacement, water balloon, oil displacement, and drive cylinders. Laboratory and field tests were performed. Laboratory tests were a little more accurate than field tests.

51. TURNBULL, W. J., and FOSTER, R., "Proof-Rolling of Subgrades." *HRB Bull. 254* (1960) pp. 12-22.

Proof-rolling of subgrades is being used by state highway departments to check the adequacy of normal compaction and to correct any deficiencies that may exist. This paper shows the cases where it will be effective and those cases where it will not. The paper also contains information that can be used to establish desirable roller characteristics and the amount that should be used for various conditions.

52. TURNER, C. H., "Chart Method Gives Unit Weight of Crushed Base Stone." *Roads and Streets,* Vol. 97, No. 12, pp. 62-63 (Dec. 1954).

A chart method is presented for determining dry unit weight of crushed stone base materials containing plus No. 4 fraction. This method gives field inspectors who check base compaction a quick, accurate, and easy method of determining the weight per cubic foot of compacted stone.

See also annotated Ref. No. 41

Gradation

53. HVEEM, F. N., "Sand-Equivalent Test for Control of Materials During Construction." *Proc. HRB,* Vol. 32 (1953) pp. 238-250.

The sand-equivalent test is used to control the quality of aggregates for untreated bases and bituminous mixes. The test is designed to enable the field engineer to quickly detect undesirable fines and is based on volumetric measurements that require about 40 min to complete. The term "sand-equivalent" expresses the thought that most soils, gravel bases, etc., are mixtures of desirable coarse particles, sand, and generally undesirable fine particles, or clay.

54. O'HARRA, W. G., "Evaluation of California Sand-Equivalent Test." *Proc. HRB*, Vol. 34 (1955) pp. 297-300.

Data from several thousand tests of base materials and mineral aggregates are portrayed in graphical form and the relationships between the California sand-equivalent test results, plasticity-index test results, and the amount passing the No 200 sieve are reported. It is concluded that the sand-equivalent test results reflect the quality of the material and that the test is of definite value as a rapid field test to determine acceptability of materials.

55. CLOUGH, R. H., and MARTINEZ, J. E., "Research on Bituminous Pavements Using the Sand-Equivalent Test." *HRB Bull. 300* (1961) pp. 1-17.

Research on the sand-equivalent test and on the correlation of sand-equivalent number with asphaltic concrete performance was performed at the University of New Mexico. To obtain the widest possible range of test values, the Highway Department furnished samples of hot-mix asphaltic concrete and hot-mix aggregate from projects located throughout the state.

Compaction Criteria

56. "Air Content Test May Improve Soil Compaction Specifications." *Surveyor and Municipal and County Eng* (London), Vol. 114, No. 3317, pp. 965-966 (Oct. 1955).

Practical trials are to be carried out on a new method of specifying the compaction of soils based on air content in conjunction with moisture content. The degree of compaction required in earthworks has certain drawbacks. A more satisfactory approach to the problem might well be to specify: (1) the moisture content range of compaction, and (2) the state of compaction to be obtained in the field in terms of a maximum percentage of air voids for the compacted soil.

57. BRUCE, R R., "An Instrument for the Determination of Soil Compactability." *Proc. Soil Science Soc. of America*, Vol. 19, No. 3, pp. 253-257 (1955).

A method is described that requires only 600 to 800 gm of soil and 1 hr of time for each bulk density-moisture curve. The impact-type compactor described can be adjusted to deliver a wide range of compaction energies

58. CHAMBLIN, B. B., JR., "Compaction Characteristics of Some Base and Subbase Materials." *HRB Bull. 325* (1962) pp. 1-21.

The compaction characteristics of base and subbase materials were obtained using a vibrating table and field compaction experiments. Unit weights were compared with those produced by standard methods. Results indicate that laboratory vibration produced densities comparable to field densities, whereas current AASHO and ASTM standard compaction test methods yield lower densities. Formulas that predict theoretical density increases from plus No. 4 material are unrealistic.

59. HUMPHRES, H. W., "A Method for Controlling Compaction of Granular Materials." *HRB Bull. 159* (1957) pp. 41-57.

A new method has been developed for establishing the maximum density values for granular soils. Values obtained agree closely with the actual field density produced by modern compaction equipment. The theoretical basis of the method is presented and the laboratory procedures, equipment, and graphical procedure used for obtaining the density versus gradation curve are described. A summary of results of more than 20 projects is included.

60. JAMES, H D., and LAREW, H. G., "A Simple Method for Obtaining Compaction Control Curves for Granular Material." *HRB Bull. 325* (1962) pp. 24-43

Presents laboratory data which show that, for the two materials studied, the method of controlling the compaction of granular materials is valid and realistic. A 6-in.-diameter mold employing a compacting hammer with free fall was used. Equipment and test procedures for directly establishing these control curves are described.

61. JOHNSON, A. W, and SALLBERG, J. R., "Principal Methods for Determining Maximum Unit Weight and Optimum Moisture Content." *HRB Bull. 319* (1962) pp. 4-20.

Various methods for determining maximum unit weight and optimum moisture content are discussed Impact and kneading-type compactors are described in addition to vibratory and static methods. Density ratio, relative density, and compaction ratio are explained. Abbreviated procedures such as the one-point compaction test and estimation of optimum moisture and maximum dry density are also discussed.

62. JOHNSON, A. W., and SALLBERG, J. R, "Methods of Determining Maximum Dry Unit Weight and Optimum Moisture Content for Materials Containing Coarse Aggregate." *HRB Bull. 319* (1962) pp. 81-98.

Compaction tests on a material is the most direct method for obtaining the maximum unit weight and optimum moisture content. However, the small compaction molds used in the standard test limit the maximum aggregate size to ¾ in.

When larger aggregates are used adjustments must be made to the final results, or to the apparatus and procedure.

63. Johnson, A. W., and Sallberg, J. R., "Methods for Estimating Moisture Content-Unit Weight Relationships." *HRB Bull 319* (1962) pp. 120-126.

Because the proper moisture content and dry unit weight of a soil are very important in earthwork construction, studies have been made to determine what relationships exist between optimum moisture content and maximum dry unit weight and the other index properties that are normally determined in routine identification tests. The studies showed some close interrelationships.

64. MacNeil, J., "New Test for Control of Cohesive Soils in Rolled-Fill." *Proc. ASCE*, Vol. 82 (1956).

A new test, called the "drop" test, has been devised to overcome the difficulties entailed in the effective control of the placing of rolled fill under modern rapid rates of construction The soil sample is compacted into a specimen ring 4 in. in diameter and 1½ in. high. It is then dropped on edge from a fixed elevation onto a concrete slab, and its reduced height above the flattened surface is measured.

65. Mainfort, R. C., and Lawton, W. L., "Laboratory Compaction Tests of Coarse-Graded Paving and Embankment Materials." *Proc HRB*, Vol. 32 (1953) pp. 555-566.

Results are presented of a laboratory study of the applicability of the Proctor type of compaction test to the compaction of coarse-graded materials Three representative granular materials were tested through a range of carefully controlled artificial gradations in which the parts of coarse and fine fractions were varied.

66. Murayamo, S., Ueshita, K., and Saito, M., "The Ball Drop Test as a Rapid Method of Measuring the CBR." *Tech. Translations*, Vol. 7, No. 10, p. 789 (1962).

The CBR-value of a subgrade can be determined immediately by measuring the diameter of the depression produced on the surface of a subgrade by a spherical ball dropped from a certain height. The testing method is related to ordinary CBR tests by theoretical and experimental studies. This method also can be used to measure the dry density and the trafficability of a soil.

67. Pettibone, H. C., and Hardin, J., "Research on Vibratory Maximum Density Test for Cohesionless Soils." A paper presented at ASTM Ann. Meeting, Denver (June 1964).

Results are presented of an investigation of vibratory methods to determine the combination of variables that would give the highest laboratory maximum density. Four electromagnetic table-type vibrators, an immersion-type concrete vibrator, and a pneumatic table-type vibrator were used. The effect on the soil density of amplitude of vibration, magnitude of surcharge, time of vibration, oven-dry and saturated soil conditions, and initial soil density were studied for seven cohesionless soils representing a wide range in gradations.

68. Ring, G. W., III, Sallberg, J. R., and Collins, W. H., "Correlation of Compaction and Classification Test Data." *HRB Bull. 325* (1962) pp. 55-75.

The results of two correlation studies are reported for a large number of soils from many parts of the United States. In the first study, compaction data are correlated with plastic limit and liquid limit. In the second, compaction data are correlated with different combinations of plastic limit, liquid limit, plasticity index, and several measures of gradation.

69. U.S. Army Corps of Engineers, "Soil Compaction Studies, Miscellaneous Laboratory Tests." *Soil Compaction Invest. Report No 5.* (June 1950).

Studies were conducted to: (1) determine a suitable method for saturating soil samples for design tests, (2) determine the size of mold required to prepare samples for the laboratory CBR tests, (3) develop a suitable method for determining the CBR-values of soils containing gravel particles larger than ¼ in., (4) develop a suitable compaction control test for cohesionless materials, and (5) develop a mechanical laboratory compactor suitable for preparation of soil samples for laboratory strength tests.

70. Stallworth, T. W., "Correlation of Field and Laboratory Compaction Data." *Proc. 6th Ala. Joint Highway Conf.* pp. 43-49 (Apr. 1963).

Field tests used a 50-ton roller to compact the test sections. Four passes produced the standard Proctor densities. Laboratory tests indicate the unconfined compressive strength at 90 percent Proctor density is twice the unconfined compressive strength of samples at 85 percent standard Proctor density. Recommends use of moisture content and unconfined compressive strength as compaction criteria rather than density.

71. Taylor, H. M., "A Pneumatic Soil Compression Device." *Proc. Soil Science Soc. of America*, Vol. 22, No. 3, pp. 271-272 (1958).

A pneumatically applied load appears to more closely approximate the vehicular compression cycle than an impact loading. A pneumatic

soil compression device useful in studying relations between load and soil compression, moisture content, and soil treatment is described

PORTLAND CEMENT CONCRETE

General

72. BUTCHER, S., "The Evaluation of Hardened Concrete." *J (Australia) Inst. of Eng.*, Vol. 30, No. 6, pp. 185-189 (June 1958).

    Reviews of the various methods that are available to determine the strength, quality, condition, and other properties of concrete subsequent to its being placed in service.

73. MAXON, G., "Suggested Quality Control Method for Highway Concrete." *Roads and Streets*, Vol. 99, No. 7, pp. 72, 74, 78, (July 1956).

    Simplified sampling plus use of the Kelly ball, Chace air meter, and Hime-Willis test are suggested as a step toward needed improvement in quality control of concrete

74. MAXWELL, A. A, "Non-Destructive Testing of Pavements." *HRB Bull 277* (1960) pp. 30-36.

    A vibratory-type machine was developed for non-destructive testing of pavements. The machine determines the wave velocity, and from this the elastic modulus or the stiffness factor of the pavement can be determined. Typical results obtained with this machine are presented.

Cement and Water Content

75 BUTLER, B. C., "Development of Instrumentation for Measuring Water and Cement Content of Fresh Concrete." *Report No EES 206-1*, Eng. Experiment Station, Ohio State Univ. (July 1963).

    Presents a proposed process for separating cement from a plastic concrete, and the determination of cement content by further centrifuging in a heavy liquid Equipment was developed to make use of the P-19 and P-21 moisture gauges of Nuclear-Chicago to determine moisture content. This equipment was developed in the laboratory and was not completely field-tested.

76. CHADDA, L. R., "The Rapid Determination of Cement Content in Concrete and Mortar." *Indian Conc. J.*, Vol. 29, No 8, pp. 258-260 (1955).

    After a large number of experiments were conducted in the laboratory it was possible to introduce two simple methods for determining cement content in concrete and mortar: (1) conductimetrics, based on the conductivity of pure water in which a known quantity of unset cement-sand mixture has been shaken, and (2) absorption, based on the differential absorption characteristics of cement and sand particles.

77. DEWAN, R. L., "The Rapid Estimation of Cement Content in Mortar and Concrete." *Indian Conc. J.*, Vol. 33, No. 4, pp. 132-133 (1959).

    The method described consists essentially in determining the calcium content of mortar and concrete. Graphs from data may be drawn

78. HIME, W. G., and WILLIS, R. A., "Method of Determination of Cement Content of Plastic Concrete" *ASTM Bull. No. 209*, pp 37-43 (Oct. 1955).

    Describes the work that has been done toward the development of an accurate and rapid quality concrete test, using the principle of heavy media separation

79. PAWLIW, J, and SPINKS, J. W. T., "Neutron Moisture-Meter for Concrete." *Canadian J. Tech.* (Ottawa), Vol. 34, pp. 503-513 (1957)

    A portable instrument for determining rapidly the total water content of a plain or lightly reinforced concrete member without destruction is described The fast neutrons from a Ra-Be source (50 mc) are converted into slow neutrons by the water molecules and are then counted with a boron trifluoride tube (2 to 4 in. long). The meter, which can be handled without exposure to excessive radiations from the source, is calibrated against concrete cylinders of known water content. The sensitivity is less than for the moisture-meter used in soils, because it is placed against only the surface of the concrete.

80. "Proposed Tentative Method of Test for Cement Content of Freshly Mixed Concrete" Subcommittee III-c of ASTM Committee C-9, *ASTM Bull. No. 239*, pp. 48-49 (July 1959).

    This method of test uses the principle of heavy liquid separation of cement from fine aggregate. This method is essentially a refinement of that first proposed by Himes and Willis The committee extended to users of the method an invitation to submit to it data as to its effectiveness.

81. WALKER, S., BLOEM, D. L., GAYNOR, R. D, and WILSON, J R, "A Study of the Centrifuge Test for Determining the Cement Content of Fresh Concrete." *Materials Research and Standards*, Vol. 1, No 6, pp. 454-460 (June 1961).

    An evaluation is given of the centrifuge test (in a heavy liquid) for cement content of plastic concrete. Refinements in procedure are discussed, along with the meticulous care needed to make the test. The small sample tested leads to the question of whether one can obtain such a small representative sample under field conditions Data are presented from laboratory tests on concretes with various cement factors.

Air Content

82. Erlin, B., "Air Content of Hardened Concrete by a High-Pressure Method." *J. Portland Cement Assn.*, Vol 4, No. 3, pp. 24-29 (Sept. 1962).

    Describes portable equipment of special design for the determination of air content of hardened concrete by a high-pressure method. Air contents determined with this apparatus, the linear traverse method, and the pressure method are compared

83. Grieb, W. E., "The AE-55 Indicator for Air in Concrete." *HRB Bull. 176* (1958) pp. 23-28.

    Tests were made in the laboratory to obtain information on the accuracy and dependability of this apparatus. The air contents of a large number of concrete mixes were determined using this indicator and the results were compared with those obtained by other methods

84 Lindsay, J. D , "Illinois Develops High-Pressure Air Meter for Determining Air Content of Hardened Concrete." *Proc. HRB*, Vol 35 (1956) pp 424-433.

    Describes the development of apparatus and test procedure for determining air content of hardened concrete, using pressure and the principles of Boyle's Law. It is a valuable addition to the product control procedure and it offers promise for use in bituminous concrete specimens.

85. Newlon, H. H., Jr., "A Field Investigation of the AE-55 Air Indicator." *HRB Bull. 305* (1961) pp. 1-13.

    The results of a statewide experiment in Virginia to compare the AE-55 air indicator for concrete with conventional pressure methods are presented Data from 835 comparative tests with various materials and operators are compared and analyzed.

Workability

86. Hughes, B. P., "Development of an Apparatus to Determine the Resistance to Segregation of Fresh Concrete." *Civil Eng. and Pub. Works Review* (London), Vol. 56, No. 658, pp. 633-634 (May 1961).

    A segregation test was devised to measure resistance of fresh concrete to segregation. The equipment consists of an upper hopper, a low hopper, an inverted cone, and an upper and lower plate beneath the cone. Segregation was determined quantitatively in terms of a "stability factor." The author states that this device, in the form in which it was tested, was not sensitive enough.

87. Kelly, J. W., and Haavik, N. E., "A Single Test for Consistency of Concrete." *ASTM Bull No. 163*, pp 70-74 (Jan. 1950).

    Describes a simple field test for consistency of plastic concrete. The test consists of observing the amount of penetration of a 30-lb metal ball of 6-in. diameter into the surface of the concrete. Results of laboratory and field tests, and comparisons with slump cone values, are given. Reference is made to similar penetration tests that had been developed in Spain, England, and Germany.

88. Kelly, J. W, and Polivka, M., "Ball Test for Field Control of Concrete Consistency." *Proc. Amer. Conc. Inst.*, Vol. 51, pp. 881-888 (1955).

    The development and use of the Kelly ball to measure workability is discussed in detail by the originator of the equipment. Comparisons are made of Kelly ball and slump cone values from extensive field tests Speed, less likelihood of personal error, and adaptability to use on undisturbed samples of concrete in buckets and forms are listed as advantages of the Kelly ball procedure.

89. Marr, R. A., Jr., and Grieb, W. E, "Use of the Kelly Ball as a Device for Measuring the Consistency of Concrete." *Pub. Roads*, Vol. 28, No. 12, pp. 266-270 (Feb. 1956).

    The Kelly ball test is a simple field method for determining the consistency of plastic concrete It is made by measuring the penetration of a 30-lb metal ball into the surface of the concrete. Data and slump correlation are presented.

90 Polatty, J. M., "New Type of Consistency Meter Tested at Allatoona Dam." *Proc. Amer. Conc. Inst.*, Vol. 46, pp 129-136 (1950).

    A "Plastograph" meter, invented by Glenway Maxon, was installed on two 4-cu-yd, rear-charging, front-discharging, tilter-type Smith mixers to measure consistency of the plastic concrete. This meter has eight "probes" inside the mixer which, when deflected, close an electric circuit that is connected to recording equipment. By experimentation, one can adjust incoming ingredients to obtain the mix consistency desired.

Strength

91. "An Accelerated Test for Cement." *Concrete and Const. Eng.*, Vol. 54, No. 10, pp. 323-324 (Oct. 1959).

    A method has been devised by which specimens tested 36 hr after they were cast gave a remarkably reliable indication of the strength that could be expected at 20 days. Data and results are presented.

92. Bullock, R. E., and Whitehurst, E. A., "Effect of Certain Variables on Pulse Velocities through Concrete." *HRB Bull. 206* (1959) pp. 37-41.

This study reports on investigations undertaken to determine the effects of variations in type of aggregate, maximum size of aggregate, percentage of paste, water-cement ratio, age, and curing conditions on pulse velocity testing

93. "Effects of Concrete Characteristics on the Pulse Velocity—A Symposium." *HRB Bull. 206* (1959) pp. 1-74

This entire bulletin contains papers on dynamic tests of concrete given at the HRB meeting in 1958. These papers include laboratory studies and field tests.

94. Green, G. W., "Test Hammer Provides New Method of Evaluating Hardened Concrete." *Proc. Amer. Conc. Inst.*, Vol. 51, pp. 249-256 (1955).

The Schmidt concrete test hammer provides a convenient method of determining the strength of nearly any concrete mass that has a smooth, flat surface. The test is nondestructive. Factors causing variations in results are briefly discussed and accuracy of results is compared with that of specimens tested in testing machines.

95. Grieb, W. E , "Use of Swiss Hammer for Estimating Compressive Strength of Hardened Concrete." *Pub. Roads*, Vol. 30, No. 2, pp. 45-52 (June 1958).

A simple and portable instrument for use in estimating the compressive strength of hardened concrete in place has been developed. The device, known as the Swiss hammer, is designed for field use. Test results are given.

96. King, J. W. H., "An Accelerated Test for the Seven and Twenty-Eight Day Compressive Strengths of Concrete." *J. Applied Chemistry*, Vol. 10, No. 6, pp. 256-262 (June 1960).

An accelerated curing procedure was evolved to allow the testing of concrete cubes at 7 hr, and, from their results, the prediction of 7- and 28-day compression strengths of concrete. This testing procedure was used on a wide range of concrete mixes with various cements. The experimentally established curves, in general, gave a predicted 28-day strength with a standard deviation of 225 psi.

97. Kolek, J., "An Appreciation of the Schmidt Rebound Hammer." *Mag. of Conc. Research* (London), Vol. 10, No. 28, pp. 27-37 (Mar. 1958).

The Schmidt rebound hammer is described and some theoretical aspects underlying the functioning of the hammer are discussed and supported by some experimental results. Procedure and limitations under different conditions are described.

98. Kozan, G. R., "Non-Destructive Testing of Concrete Pavements." *Proc. HRB*, Vol. 34 (1955) pp. 368-375.

One of the principal factors in determining the allowable wheel load of existing pavements is the flexural strength of the concrete. Longitudinal wave velocities through a selected group of concrete test beams and through a slab in situ were determined with an internal timer, and flexural strength values were predicted from formulas.

99. Malhotra, V. M., Zoldners, N. G., and Lapinas, R., "Accelerated Test for Determining the 28-Day Compressive Strength of Concrete." *Mines Branch Research Report R-134*, Dept. of Mines and Tech. Surveys, Ottawa (Oct 1964).

Results of accelerated curing of concrete test cylinders by a boiling-water method are presented. The method consists of standard moist-curing of specimens for 24 hr, followed by boiling for 3½ hr, and testing for compression 1 hr later. Over 1,500 cylinders were prepared from various mixes prepared in laboratory mixers and in ready-mix plants. Correlation was established between accelerated test results and standard-cured test values. An accuracy of about ±12 percent was experienced in predicting 28-day compression strengths from 28½-hr accelerated cured specimens.

100. Meyer, R , "Eight Years of Pulse Velocity Tests on Concrete Pavements in Kansas." *HRB Bull. 206* (1959) pp 31-36.

For 8 years, the Kansas Highway Commission investigated the changes in pulse velocity which occurred with the changes in concrete quality. A soniscope was used for making these tests. Results are given and observations are made.

101. Meyer, R. C., "Dynamic Testing of Concrete Pavements with the Soniscope." *Proc. HRB*, Vol. 31 (1952) pp. 234-245.

The soniscope is an electronic instrument developed to measure pulse velocity of high-frequency sound waves through concrete. From this velocity the dynamic modulus of elasticity can be determined.

102. Mitchell, L. J., and Hoagland, G. G., "Investigation on the Impact-Type Concrete Test Hammer." *HRB Bull. 305* (1961) pp 14-27.

Describes a series of tests designed to determine the reliability of results, the feasibility of use, and the practical applications of the test hammer in construction control. Results are compared with other investigations.

103. "Non-Destructive Testing of Concrete." *HRB Bibliography 33* (1963).

Contains references to over 470 articles appearing between 1889 and 1962 on nondestructive testing of concrete.

104. Wesche, K., "Some Applications of Ultrasonics in Concrete Testing." *Building Science Abstracts*, Vol. 28, No. 11, p. 322 (Nov. 1955).

Ultrasonic methods can be applied to test specimens to determine the dynamic modulus of elasticity, to test transverse and torsional frequencies, to study cracking, and to locate voids in concrete in structures. A more exact determination requires the ball impact test to supplement the foregoing.

105. Zoldners, N. G., "Calibration and Use of Impact Test Hammer." *Proc. Amer. Conc. Inst.*, Vol. 54, pp. 161-168 (1958).

The Schmidt concrete test hammer is based on empirical relationship between the strength of concrete and the rebound of a steel plunger which is impinged against the face of the concrete under controlled conditions. This paper serves as an addendum to an earlier *ACI Journal* paper which describes the test hammer, its calibration, and use.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Rep. No.	*Title*
—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj 4-3(2)), 81 p., $1.80
1	Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Proj. 6-8), 56 p., $2.80
2	An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1 80
2A	Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00
3	Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Proj. 3-5), 36 p., $1.60
4	Non-Chemical Methods of Snow and Ice Control on Highway Structures (Proj. 6-2), 74 p, $3.20
5	Effects of Different Methods of Stockpiling Aggregates—Interim Report (Proj. 10-3), 48 p., $2.00
6	Means of Locating and Communicating with Disabled Vehicles—Interim Report (Proj. 3-4), 56 p. $3.20
7	Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Proj. 1-2), 29 p., $1.80
8	Synthetic Aggregates for Highway Construction (Proj. 4-4), 13 p., $1.00
9	Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Proj. 3-2), 28 p., $1.60
10	Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Proj. 1-4), 31 p., $2.80
11	Effect of Control Devices on Traffic Operations—Interim Report (Proj 3-6), 107 p., $5.80
12	Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Proj. 4-3(1)), 47 p., $3.00
13	Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Proj. 2-5), 43 p., $2.80
14	Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Proj. 10-5), 32 p., $3.00
15	Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Proj. 4-3(2)), 66 p., $4 00
16	Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Proj. 6-3), 21 p., $1.60
17	Development of Guidelines for Practical and Realistic Construction Specifications (Proj. 10-1), 109 p., $6.00
18	Community Consequences of Highway Improvement (Proj 2-2), 37 p., $2.80
19	Economical and Effective Deicing Agents for Use on Highway Structures (Proj. 6-1), 19 p., $1.20

* Highway Research Board Special Report 80

Rep. No.	*Title*
20	Economic Study of Roadway Lighting (Proj. 5-4), 77 p., $3.20
21	Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Proj. 1-5), 30 p., $1.40
22	Factors Influencing Flexible Pavement Performance (Proj. 1-3(2)), 69 p., $2.60
23	Methods for Reducing Corrosion of Reinforcing Steel (Proj. 6-4), 22 p., $1.40
24	Urban Travel Patterns for Airports, Shopping Centers, and Industrial Plants (Proj. 7-1), 116 p., $5.20
25	Potential Uses of Sonic and Ultrasonic Devices in Highway Construction (Proj. 10-7), 48 p, $2.00
26	Development of Uniform Procedures for Establishing Construction Equipment Rental Rates (Proj. 13-1), 33 p., $1.60
27	Physical Factors Influencing Resistance of Concrete to Deicing Agents (Proj. 6-5), 41 p., $2.00
28	Surveillance Methods and Ways and Means of Communicating with Drivers (Proj. 3-2), 66 p., $2.60
29	Digital-Computer-Controlled Traffic Signal System for a Small City (Proj. 3-2), 82 p., $4.00
30	Extension of AASHO Road Test Performance Concepts (Proj. 1-4(2)), 33 p., $1.60
31	A Review of Transportation Aspects of Land-Use Control (Proj. 8-5), 41 p., $2.00
32	Improved Criteria for Traffic Signals at Individual Intersections (Proj. 3-5), 134 p., $5.00
33	Values of Time Savings of Commercial Vehicles (Proj. 2-4), 74 p., $3.60
34	Evaluation of Construction Control Procedures—Interim Report (Proj. 10-2), 117 p., $5,00
35	Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests (Proj. 1-3(3)), 117 p., $5.00
36	Highway Guardrails—A Review of Current Practice (Proj. 15-1), 33 p., $1.60
37	Tentative Skid-Resistance Requirements for Main Rural Highways (Proj. 1-7), 80 p., $3.60
38	Evaluation of Pavement Joint and Crack Sealing Materials and Practices (Proj. 9-3), 40 p., $2.00
39	Factors Involved in the Design of Asphaltic Pavement Surfaces (Proj. 1-8), 112 p., $5.00
40	Means of Locating Disabled or Stopped Vehicles (Proj. 3-4(1)), 40 p., $2.00
41	Effect of Control Devices on Traffic Operations (Proj. 3-6), 83 p., $3.60
42	Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60
43	Density and Moisture Content Measurements by Nuclear Methods (Proj 10-5), 38 p., $2.00
44	Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40
45	Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40
46	Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60
47	Accident Rates as Related to Design Elements of Rural Highways (Proj. 2-3), 173 p., $6.40
48	Factors and Trends in Trip Lengths (Proj. 7-4), 70 p, $3 20
49	National Survey of Transportation Attitudes and Behavior—Phase I Summary Report (Proj. 20-4), 71 p., $3.20

Rep. No.	*Title*
50	Factors Influencing Safety at Highway-Rail Grade Crossings (Proj. 3-8), 113 p., $5.20
51	Sensing and Communication Between Vehicles (Proj. 3-3), 105 p., $5.00
52	Measurement of Pavement Thickness by Rapid and Nondestructive Methods (Proj. 10-6), 82 p., $3.80
53	Multiple Use of Lands Within Highway Rights-of-Way (Proj. 7-6), 68 p., $3.20
54	Location, Selection, and Maintenance of Highway Guardrails and Median Barriers (Proj. 15-1(2)), 63 p., $2.60
55	Research Needs in Highway Transportation (Proj. 20-2), 66 p., $2.80
56	Scenic Easements—Legal, Administrative, and Valuation Problems and Procedures (Proj. 11-3), 174 p., $6.40
57	Factors Influencing Modal Trip Assignment (Proj. 8-2), 78 p., $3 20
58	Comparative Analysis of Traffic Assignment Techniques with Actual Highway Use (Proj. 7-5), 85 p., $3.60
59	Standard Measurements for Satellite Road Test Program (Proj. 1-6), 78 p., $3.20
60	Effects of Illumination on Operating Characteristics of Freeways (Proj. 5-2) 148 p., $6.00
61	Evaluation of Studded Tires—Performance Data and Pavement Wear Measurement (Proj. 1-9), 66 p., $3.00
62	Urban Travel Patterns for Hospitals, Universities, Office Buildings, and Capitols (Proj. 7-1), 144 p., $5.60
63	Economics of Design Standards for Low-Volume Rural Roads (Proj. 2-6), 93 p., $4.00
64	Motorists' Needs and Services on Interstate Highways (Proj. 7-7), 88 p, $3.60
65	One-Cycle Slow-Freeze Test for Evaluating Aggregate Performance in Frozen Concrete (Proj. 4-3(1)), 21 p., $1.40
66	Identification of Frost-Susceptible Particles in Concrete Aggregates (Proj. 4-3(2)), 62 p., $2.80
67	Relation of Asphalt Rheological Properties to Pavement Durability (Proj. 9-1), 45 p., $2.20
68	Application of Vehicle Operating Characteristics to Geometric Design and Traffic Operations (Proj. 3-10), 38 p, $2.00
69	Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects (Proj. 10-2A), 58 p., $2.80
70	Social and Economic Factors Affecting Intercity Travel (Proj. 8-1), 68 p., $3.00
71	Analytical Study of Weighing Methods for Highway Vehicles in Motion (Proj. 7-3), 63 p., $2.80
72	Theory and Practice in Inverse Condemnation for Five Representative States (Proj. 11-2), 44 p., $2.20
73	Improved Criteria for Traffic Signal Systems on Urban Arterials (Proj. 3-5/1), 55 p., $2.80
74	Protective Coatings for Highway Structural Steel (Proj. 4-6), 64 p., $2.80
74A	Protective Coatings for Highway Structural Steel—Literature Survey (Proj. 4-6), 275 p., $8.00
74B	Protective Coatings for Highway Structural Steel—Current Highway Practices (Proj. 4-6), 102 p., $4.00
75	Effect of Highway Landscape Development on Nearby Property (Proj. 2-9), 82 p., $3.60

Rep No.	*Title*
76	Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements (Proj. 1-5(2)), 37 p., $2.00
77	Development of Design Criteria for Safer Luminaire Supports (Proj. 15-6), 82 p., $3.80
78	Highway Noise—Measurement, Simulation, and Mixed Reactions (Proj 3-7), 78 p., $3.20
79	Development of Improved Methods for Reduction of Traffic Accidents (Proj. 17-1), 163 p., $6.40
80	Oversize-Overweight Permit Operation on State Highways (Proj. 2-10), 120 p., $5.20
81	Moving Behavior and Residential Choice—A National Survey (Proj. 8-6), 129 p., $5.60
82	National Survey of Transportation Attitudes and Behavior—Phase II Analysis Report (Proj. 20-4), 89 p., $4.00
83	Distribution of Wheel Loads on Highway Bridges (Proj. 12-2), 56 p., $2.80
84	Analysis and Projection of Research on Traffic Surveillance, Communication, and Control (Proj. 3-9), 48 p., $2.40
85	Development of Formed-in-Place Wet Reflective Markers (Proj. 5-5), 28 p., $1.80
86	Tentative Service Requirements for Bridge Rail Systems (Proj. 12-8), 62 p., $3.20
87	Rules of Discovery and Disclosure in Highway Condemnation Proceedings (Proj. 11-1(5)), 28 p., $2.00
88	Recognition of Benefits to Remainder Property in Highway Valuation Cases (Proj. 11-1(2)), 24 p., $2.00
89	Factors, Trends, and Guidelines Related to Trip Length (Proj. 7-4), 59 p., $3.20
90	Protection of Steel in Prestressed Concrete Bridges (Proj. 12-5), 86 p., $4.00
91	Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research (Proj. 16-1), 70 p., $3.20
92	Valuation and Condemnation of Special Purpose Properties (Proj. 11-1(6)), 47 p., $2.60
93	Guidelines for Medial and Marginal Access Control on Major Roadways (Proj. 3-13), 147 p., $6.20
94	Valuation and Condemnation Problems Involving Trade Fixtures (Proj. 11-1(9)), 22 p., $1.80
95	Highway Fog (Proj. 5-6), 48 p., $2.40
96	Strategies for the Evaluation of Alternative Transportation Plans (Proj. 8-4), 111 p., $5.40
97	Analysis of Structural Behavior of AASHO Road Test Rigid Pavements (Proj. 1-4(1)A), 35 p., $2 60
98	Tests for Evaluating Degradation of Base Course Aggregates (Proj. 4-2), 98 p. $5.00
99	Visual Requirements in Night Driving (Proj. 5-3), 38 p., $2.60
100	Research Needs Relating to Performance of Aggregates in Highway Construction (Proj. 4-8), 68 p., $3 40
101	Effect of Stress on Freeze-Thaw Durability of Concrete Bridge Decks (Proj. 6-9), 70 p., $3.60
102	Effect of Weldments on the Fatigue Strength of Steel Beams (Proj. 12-7), 114 p., $5.40
103	Rapid Test Methods for Field Control of Highway Construction (Proj. 10-4), 89 p., $5.00

Rep
No. *Title*

Synthesis of Highway Practice

1 Traffic Control for Freeway Maintenance (Proj. 20-5, Topic 1), 47 p., $2.20
2 Bridge Approach Design and Construction Practices (Proj. 20-5, Topic 2), 30 p., $2.00
3 Traffic-Safe and Hydraulically Efficient Drainage Practice (Proj. 20-5, Topic 4), 38 p., $2.20
4 Concrete Bridge Deck Durability (Proj. 20-5, Topic 3), 28 p., $2.20

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by President Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U. S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Federal Highway Administration, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.

HIGHWAY RESEARCH BOARD
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue Washington, D. C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970

003901
LIBRARIAN
NATL ACADEMY SCIENCES
P.O. STOP 44