NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **25**

POTENTIAL USES OF SONIC AND ULTRASONIC DEVICES IN HIGHWAY CONSTRUCTION

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

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REPORT 25

POTENTIAL USES OF SONIC AND ULTRASONIC DEVICES IN HIGHWAY CONSTRUCTION

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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 Bureau of Public Roads, United States Department of Commerce.

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.

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 U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, 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 research plan. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

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FOREWORD

By Staff

Highway Research Board

In general, there is little significant experience available concerning the application of mechanical vibrational energy, either sonic or ultrasonic, in the field of civil engineering and, more specifically, in the area of highway engineering. Inasmuch as this report contains the results of a state-of-the-art survey and a study of the feasibility of applications to highway construction, it will be of most interest to research engineers. Experiments to determine the applicability of vibrational energy to the preparation and evaluation of highway materials are described, and recommendations have been made for measures needed to advance the art.

The use of sonic and ultrasonic devices is well known in such fields as dentistry, food preparation, metallurgy, surface finishing, physiotherapy, and nondestructive testing. Present practical applications and results of recent experiments indicate that there is a wide range for potential use in many aspects of highway engineering. These include pile driving, compaction, sampling, drilling, cutting, excavation, clearing, demolition, joint construction, and many others, most of which impose horsepower requirements which cannot presently be met. Because there is considerable variation between the energy levels now available and those necessary, there is a need for practical experiments to establish the capabilities and limitations which might be encountered at the necessary energy levels, rather than assume that the unique effects associated with current energy levels can also be expected when there is an increase by factors of ten or more. Further, the fundamental aspects of energy propagation must be investigated for a particular frequency selected to accomplish a specific objective if maximum effectiveness and economy are to be realized.

This problem has been researched by the Ohio State University through a combination of a study of the present use of sonic and ultrasonic frequencies in all fields and a feasibility study of possible applications in highway construction. A thorough search has been made of literature resulting from a variety of related endeavors, and both correspondence and direct contacts have been made with active and knowledgeable persons in the fields of research, engineering, highway construction, ultrasonic physics, ultrasonic power and measurement systems, nondestructive testing, and others. An extensive bibliography, a great deal of which is annotated, has resulted from this survey but is not included in this publication. With the continually growing interest in the subject matter, this compilation of pertinent information should be of considerable use to other researchers, and copies as received from the research agency will be made available on a loan basis upon request to the National Cooperative Highway Research Program.

Although the frequencies of interest in this study are between 60 and

25,000,000 cycles per second, the work was necessarily limited to a range between the lower limit and 10,000 cycles per second because the transducers available at the beginning of the study possessed only small power capacities. Engineering studies of vibratory compaction of highway materials, especially soils, were first made in view of the promise in this area, and experiments were conducted which employed piezoelectric and air-driven rotating-ball transducers. Limited experiments in mixing and compacting granular materials and asphaltic mixtures were also performed.

It was never intended that this project would progress beyond indicating the feasibility of utilizing sonic and ultrasonic energy in highway construction; therefore, the fact that this is a final report does not signify that solutions to all pertinent problems have been found. Rather, the feasibility has been established within limits, and the critical problems which must be overcome before the concepts can be translated into useful equipment and procedures have been indicated. It has been established that these concepts cannot be put into the widespread use desired until sonic systems of much greater power, on the order of 10 to 1,000 horsepower, are available. It is considered that further work in this direction is warranted. In conjunction with this effort, it is also considered that extensive research is needed to establish the reaction of highway materials to the frequencies being proposed inasmuch as there is a lack of knowledge as to the effects on the fundamental properties of the materials.

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ACKNOWLEDGMENTS

The research described in this report was administered through the Engineering Experiment Station, Transportation Engineering Center, The Ohio State University. The project was under the general supervision of Dr. F. Moavenzadeh, Assistant Professor of Civil Engineering, and Dr. R. C. McMaster, Director, Ultrasonic Research Laboratory, Department of Welding Engineering.

The following contributed to various phases of the project: W. E. McKibben, Associate Supervisor, Ultrasonic Research Laboratory, Department of Welding Engineering; C. C. Libby, Research Associate, Engineering Experiment Station, The Ohio State University; Fred Houck, Technical Assistant, Ultrasonic Research Laboratory; B. N. Jagannath, Research Assistant, Department of Civil Engineering; and Paul Benson, Graduate Assistant, Department of Civil Engineering. Mr. Benson was primarily in charge of the experimental work of this study.

POTENTIAL USES OF SONIC AND ULTRASONIC DEVICES IN HIGHWAY CONSTRUCTION

SUMMARY

Laboratory research in sonics and ultrasonics during the past half century has demonstrated many unique effects and potential uses for such vibratory energy. Unfortunately, such research was done at low levels (1 to 1,000 watts), and relatively small effects were observed. To date, no major industrial firm or other facility has developed sonic and ultrasonic power supplies and transducers operable in the range of 10 to 1,000 hp needed for most highway construction applications. As a consequence, practical application has lagged behind.

Extrapolation from these laboratory experiments to full-scale highway construction applications is potentially dangerous and misleading. Practical tests with adequate power levels are essential to the determination of the capabilities and limitations of vibratory energy in highway engineering. The recognized need for a thorough review of the area, in combination with some practical tests, is the basis for the research work reported here, which was initiated to evaluate (a) the present use of high-frequency vibrations in various industrial and scientific fields, and (b) the feasibility of possible applications of sonic and ultrasonic mechanical vibrational energy in highway engineering and construction. The study was to be directed specifically toward evaluation of potential applications of sonic energy (60 cps to 25 Mc) and not toward development of power supplies or transducers, which was the subject of another project by the research agency.

This investigation has resulted in an extensive survey of the literature on past developments in the field of sonic and ultrasonic research and applications of vibratory energy in civil engineering applications. In general, these references fall into two basic classes: (a) evaluations of low-frequency vibration systems with civil engineering applications, and (b) research with low-power high-frequency vibration systems which were generally not applicable to civil engineering applications. In both instances, the beneficial effects of sonic energy in soil compaction and other highway engineering applications have been minimal because the sonic power levels were quite inadequate for the basic functions required in highway engineering applications. (Sonic power requires both high force amplitudes and high audio frequencies if high power levels (several horsepower) are to be provided to the work materials.) Thus, although many possible beneficial effects can be demonstrated by low-power experiments, the magnitudes of these benefits remain too low to be attractive in practical applications.

In this preliminary research investigation, conducted with sonic transducer and vibration-excitation systems available during the research period, similar limitations existed. The true levels of sonic power provided to the work materials in these tests were typically in the range from 10 to 100 watts. This level of sonic power was so low that beneficial effects of sonic power were very small in comparison with the natural properties of materials and the beneficial effects of high

static loads used with conventional methods. Despite these power limitations, some significant effects were observed, but the magnitudes of these effects were minimal. Tests included standard and vibratory compaction of highway materials, especially soils, and limited tests on mixing and compaction of other highway materials such as asphaltic mixtures and granular materials.

Since the completion of the study described in this report, research activities in the Ultrasonic Power Laboratory of The Ohio State University, under sponsorship of the Ohio Department of Highways and the U. S. Bureau of Public Roads, have made strides in development of practical high-power sonic transducers.

Low-frequency high-force transducer systems have been developed to apply forces up to 6,000 lb, at frequencies in the range of 60 cps. These have been demonstrated as remarkably effective in increasing the capacity of earth and snow removal by tests on small (garden-type) tractors. Similar experiments with a full-scale farm tractor indicated equally beneficial effects.

In addition, preliminary tests with portland cement concrete indicated that sonic mixing and placement of relatively dry mixes resulted in doubling the compressive strength of cylindrical test specimens after seven days of curing, and a final strength improvement (after 28 days) of 25%. These tests indicate a potential benefit of great economic significance in highway engineering. With advanced transducer systems now available, it is probable that further improvement in properties could be attained.

Parallel development of high-power high-frequency (10,000 cps) piezoelectric transducers has shown equally remarkable results in this more recent research. Sonic motors have now been developed to provide 15 hp of output with better than 95% power efficiency. These units generate more than 2 hp per cubic inch of piezoelectric material. The attached steel force-concentration members can readily provide output force densities exceeding the yield points of structural steels (30,000 to 45,000 psi). These tests provide a remarkable demonstration of the effects of high sonic power levels upon materials. In their present stage of development, these sonic motors surpass conventional electrical and internal combustion motors in every basic operating characteristic. Size, cost, and maintenance are greatly reduced because the units have no moving parts and are extremely rugged. Power outputs per unit weight or volume, and efficiency, far exceed those of comparable conventional driving systems.

In comparison with the sonic exciters used in the experimental work described in this report (providing power outputs of a few pounds of force at low frequency, and power outputs of less than 100 watts at high frequencies), the newly developed sonic exciters provide output power and force gains of more than 1,000 times. With such transducers it is evident that the small beneficial effects due to vibration reported in these preliminary tests could be vastly enhanced. An intensive study with high-output sonic devices is urgently needed to supplement this early investigation.

CHAPTER ONE

INTRODUCTION

Laboratory research in sonics and ultrasonics during the past half century has demonstrated many unique effects and potential uses for such vibratory energy. Unfortunately, such research was done at low levels (1 to 1,000 watts), and relatively small effects were observed. To date, no major industrial firm or other facility has developed sonic and ultrasonic power supplies and transducers operable in the range of 10 to 1,000 hp needed for most highway construction applications. As a consequence, practical application has lagged behind, with the possible exceptions of vibratory pile driving with rotating eccentric-weight motors, cavitation drilling systems for small parts of hard materials, ultrasonic welding of thin-gage metals, military sonar systems, and nondestructive testing. Extrapolation from these laboratory experiments to full-scale highway construction applications is potentially dangerous and misleading. Practical tests with adequate power levels are essential to the determination of the capabilities and limitations of vibratory energy in highway engineering. The recognized need for a thorough review of the area, in combination with some practical tests, is the basis for the research work covered by this report.

OBJECTIVES

Research under the current project was initiated to evaluate (a) the present use of high-frequency vibrations in various industrial and scientific fields, and (b) the feasibility of possible applications of sonic and ultrasonic mechanical vibrational energy in highway engineering and construction. The study was to be directed specifically toward evaluation of potential applications of sonic energy (60 cps to 25 Mc) and not toward development of power supplies or transducers. (Sonic and ultrasonic transducers and power supplies are being developed in an existing project sponsored by the Ohio Department of Highways and the U. S. Bureau of Public Roads, in the Ultrasonic Research Laboratory, The Ohio State University.)

Therefore, a thorough study was made of technical literature and research reports on present use of sonic and ultrasonic energy. Promising novel methods, as well as known methods, were reviewed. Applications of sonic energy to preparation and evaluation of highway materials were studied experimentally.

ORGANIZATION AND RESEARCH PLAN

The research program was administered through the Engineering Experiment Station, Transportation Engineering Center, The Ohio State University. The Ultrasonic Research Laboratory was responsible for (a) analyzing sonic and ultrasonic systems; (b) supplying sonic power supplies, transducers, attachment devices and tools, instrumentation, and control systems; and (c) conducting sonic tests and measurements. The Civil Engineering Department was responsible for (a) selection of test procedures, (b) preparation of materials, (c) testing materials and specimens treated ultrasonically, (d) evaluation of the capabilities and limitations of application, and (e) evaluation of future potentials of ultrasonic energy and measurement systems for use in highway construction.

Studies of past developments and of present use of vibratory energy and measurement systems, and of recent experiments in all fields of ultrasonic and sonic research, were conducted jointly, with each group assuming responsibility for the areas within its greatest skill and experience.

During this research, ultrasonic power systems and instrumentation used were limited to those developed in other existing research projects; further development of ultrasonic equipment or of costly instrumentation was not contemplated within the scope of the project.

Phase I—Study of Present Use

The study of present uses of sonic and ultrasonic energy in various fields was conducted by (a) thorough search of technical literature, research reports, government and other agency reports, patents, and other available sources; (b) correspondence with those most active in such fields; and (c) direct personal contacts with research, engineering, highway construction, and other personnel which were sources of valid information in such fields. Wherever feasible, copies of pertinent documents containing useful information were procured and microfilmed by low-cost techniques.

Searches in the field of civil and highway engineering were made by the senior staff members of the Civil Engineering Department assigned to the project. Searches in the field of ultrasonic physics, ultrasonic power and measurement systems, nondestructive testing, and related areas were made by senior staff members of the Ultrasonic Research Laboratory assigned to the project. The results of these searches have been coordinated and evaluated and summary reports have been prepared in each significant area of potential application. Selected bibliographies of useful documents and sources of information pertinent to the various aspects of the work are available to qualified researchers on a loan basis from the National Cooperative Highway Research Program.*

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* The three volumes comprise the following:

1. *Civil Engineering Application of Vibrations and Wave Propagation in Solid Media: An Annotated Bibliography.* This volume contains abstracts of more than 500 articles in four major subdivisions:

(a) Nondestructive testing of materials, in particular ultrasonic and sonic methods.

Phase II—Feasibility Studies of Possible Application

As early as justified by the results of the study of present use and in accordance with availability of sonic and ultrasonic equipment suitable for application tests, engineering studies and experimental evaluations were made in selected areas of application of sonic and ultrasonic devices to highway construction. In general, such studies were made by the civil engineering staff members, who selected application areas to be evaluated, planned engineering analyses and laboratory tests as needed to provide essential data, prepared materials and test specimens on small-scale application test setups, supervised ultrasonic testing or treatment, evaluated results of tests, and made final destructive tests on materials or specimens, as needed, to permit comparison with conventional methods of highway engineering.

For each such study, the ultrasonic engineering staff provided ultrasonic engineering services and evaluations, set up and operated necessary ultrasonic equipment and instrumentation, measured power or vibration amplitude levels, modified equipment as needed for optimum performance, and evaluated and reported on ultrasonic engineering phases of the investigation.

Equipment and Facilities

Facilities available for the research included those of the Engineering Experiment Station laboratories under the direction of the Transportation Engineering Center, those of the Ultrasonic Research Laboratory in the Department of Welding Engineering, and laboratories of the Department of Civil Engineering appropriate for preparation and testing of highway materials, specimens, and structures. In addition, the libraries of various departments of The Ohio State University, Chemical Abstracts Services, Battelle Memorial Institute, and others were searched.

Also vital to the experimental work was cooperation by the Ohio Department of Highways and the U. S. Bureau of Public Roads in authorizing rental of ultrasonic equipment and instrumentation procured or developed during projects under their sponsorship, under conditions that did not interfere with work on their projects.

LITERATURE SEARCH

An important phase of this investigation was a thorough search of literature and patents on sonic and ultrasonic power devices, systems, and applications. Work on this phase was carried on intensively during the first half of the investigation, and continued until all available literature sources had been covered completely. Thereafter, the search was continued as needed to include new sources of information as these became available.

The search included the following major phases:

1. United States patents on sonic and ultrasonic power transducers, power supplies and controls, application systems, and industrial applications of sonic energy.

2. Chronological searches, page by page, of major English language journals for the period from 1925 to date, for all pertinent articles and data on sonic and ultrasonic power devices, effects, applications, designs, theory, and experiments.

3. Search and recording of all major textbooks, treatises, monographs, summaries, reports, theses, and other collections of data and information on sonic and ultrasonic power systems and their applications.

4. Selection of outstanding foreign language textbooks, reports, theses, containing valuable technical information, data on design, application, theory, materials, and other information on sonic and ultrasonic power systems. Where available, original material was procured, recorded, and the most valuable sections selected for later translation as needed. Where English translations were available, these were procured if feasible, and analyzed and recorded.

5. Reports were sought from United States Government agencies, industrial and scientific research institutes, and industrial research laboratories. Solicitation by personal contact and by mail correspondence was employed as appropriate.

6. Technical information on products and materials for sonic and ultrasonic transducers and power systems, and on application systems, was procured from industrial firms engaged in production and commercial distribution of materials, components, power supply and control equipment, sonic and ultrasonic systems and services, by mail requests for available literature and data.

7. Sources so obtained were evaluated, and particular search was made for the most valuable references given in basic textbooks, technical articles, and other sources.

Permanent records were made of all patent and literature reference materials obtained, by microfilm recording with a low-cost microfilm system. Recorded data were organized effectively for rapid retrieval and continuing use during research. All data files were maintained in the research area for use by all research personnel associated with the investigation. When necessary, full-size copies of microfilmed document pages were reproduced at low cost by verifax or xerographic methods. In addition, drawings and graphs were reproduced by tracing from projected images.

To reduce the cost of indexing, the microfilm files were organized for rapid retrieval of information. Individual rolls of microfilm were used for major classification of types of document, the documents in each classification being numbered sequentially on the roll of microfilm.

(b) Wave propagation, dynamic testing, and effect of vibration on superstructure.
(c) Effect of vibration on properties of materials.
(d) Seismic methods of subsurface exploration.

2. *Ultrasonic Methods of Nondestructive Testing: Selected Bibliography.*

3. *Ultrasonic Power Systems and Their Applications in Science and Industry: Selected Bibliography.*

CHAPTER TWO

SONIC TRANSDUCER SYSTEMS

The energy of mechanical vibrations of sonic and ultrasonic frequencies has unique properties and effects. Its capabilities merit consideration for potential applications in highway construction and in other industrial uses. This form of energy has been largely unexploited to date. Yet it bears the same relation to statics or low-frequency vibrations that high-frequency electromagnetic waves have in respect to direct current and power-frequency circuits in electrical apparatus.

Exploitation of the higher-frequency ranges in electrical devices has led to advances such as radio, television, microwave communication, radar, and electronic control and computation systems in low-power systems, and to induction heating, welding, and advanced power sources in higher-power applications. Such systems today represent a major portion of the electrical industry of the nation.

Mechanical systems used in industry today are comparable to the electrical systems used in 1900. They are generally limited to static structures (often of considerable complexity) and to low-frequency devices such as air hammers or vibrators. Higher-frequency mechanical vibrations have usually been considered as annoyances to be avoided, as in noise reduction programs. Few industrial uses have been developed for sonic and higher frequencies of mechanical energy.

SONIC ENERGY

Sonic energy refers to the frequency range of mechanical vibrations audible to the human ear, roughly from 16 to perhaps 20,000 cps. Ultrasonic energy refers to frequencies above the limit of human audibility, or above about 20,000 cps. Waves with much higher frequencies, from about 50,000 cps to more than 25 Mcps (megacycles per second) are used in nondestructive tests of engineering materials, to locate hidden discontinuities and defects.

No fundamental differences, other than the frequency of vibration and the resultant wavelengths in various materials, exist between lower- and higher-frequency mechanical vibrations. However, as frequency increases, the local accelerations associated with the wave motions are greatly increased, for any given amplitude of vibration. The attenuation (by absorption and scattering of energy) of vibratory waves tends to increase with frequency, and may become critical if particle size in the medium approaches or exceeds the wavelength. Frequency must be selected for maximum effectiveness and economy, for each type of industrial application.

SONIC TRANSDUCERS

Energy transducers are devices that convert one form of energy into another. Electric motors are transducers that convert electric energy into mechanical energy. Many sonic and ultrasonic transducers also convert electric energy into mechanical vibrational energy.

Piezoelectric transducers (such as quartz, barium titanate, and lithium sulfate monohydride) deform mechanically when subjected to an electric field or voltage. Because of their fragility, their use is often limited to high-frequency low-power applications such as ultrasonic nondestructive testing.

Magnetostrictive transducers deform mechanically when magnetized. Laminations of A-nickel, for example, contract when magnetized. Because of the strength of such metallic materials, they can exert or withstand high mechanical force. Laminated nickel magnetostrictive transducers, for example, can provide dynamic output forces of the order of 5,000 psi without early fatigue failure. A typical small transducer of this type (about 4 in. long by 2 in. square) could provide forces of the order of 20,000 lb at a frequency near 20,000 cps. Operating at about 65% efficiency, this small transducer could provide an output near 1 hp. Larger magnetostrictive transducers have been built to provide output dynamic forces of 100,000 lb (with a ⅛-in. diameter core), with a rating of the order of 100 hp.

Such sonic motors can be extremely rugged and serviceable because they consist only of a laminated metallic core with exciting windings like those of an electrical transformer, and have no internal moving parts or bearings. They can actually be welded into massive structures, if desired, and can support considerable static force.

Magnetostrictive transducers of this type are suitable for applications involving high static and dynamic force levels. However, their output displacements or relative movements are very small, amounting to about 200 μin. per inch of transducer length. Their lengths vary inversely with their operating frequencies, because they behave like columns in half-wave resonance. That is, a column 1 in. long would operate at about 80,000 cps, and an 8-in. long unit would operate near 10,000 cps; to provide 1,000 cps, the column would be 6⅓ ft long.

DEVELOPMENT OF SONIC TRANSDUCER SYSTEMS

The work done with sonic transducers in this program was necessarily limited to use of available units of small power capacities operating in the frequency range of 60 cps to 10 kcps, available at the beginning of the program or developed during the one-year period of this investigation. Two basic types were employed—rotating-ball, air-driven, commercially-available mechanical vibration transducers, and piezoelectric transducers of 1/10- to 1/3-hp rating at 10 kcps available from the related project. Since the completion of the present investigation, power levels of the order of 5 hp have been attained at 10 kcps in the related

project. These experimental transducer designs were not available, however, for use during the present investigation of applications of sonic energy.

LOW-FREQUENCY MECHANICAL TRANSDUCERS

Low-frequency high-amplitude vibration inducers are manufactured and are available in many size ranges. In many cases, they can be produced in a great variety of frequency and amplitude ranges and combinations of these ranges for specific applications. Frequency ranges vary from a few to many thousands of revolutions per minute. Force ranges vary from a few ounces to several thousands of pounds. Self-contained units can be purchased which are immediately ready for use. Of the many types of vibration-inducing transducers produced, the two considered as best suited for this study are the rotating-ball and the rotating-mass types, powered either electrically or pneumatically.

Pneumatic Rotating-Ball Transducers

The air-driven rotating-ball transducer consists of a hollow circular housing with a suitable mounting bracket and fitted internally with a circular race of wear-resistant material. Into this race is inserted the proper size ball, also of wear-resistant material. The housing is drilled and tapped for connection to an air supply, and also drilled to provide an exhaust port for the expended air.

Vibrations produced by the rotation of the ball in the race are transmitted to the work through the attaching bracket. The vibrations produced by this type of transducer are of a circular nature and can only be partially controlled in direction by the method of mounting the transducer.

In many cases the exhaust air can be utilized to perform cooling and cleaning operations in connection with work being done.

Rotating-Mass Transducers

Rotating-mass transducers operate on the same basic principle as the ball type, but greater vibration amplitudes are achieved by the use of eccentrically-mounted masses of various sizes in place of the ball. This type of transducer can be powered by an electric motor or a gasoline engine, as well as by a pneumatic system. Suitable mounting brackets are attached to the housing to fit the desired type of drive system. A transducer of this type can be con-

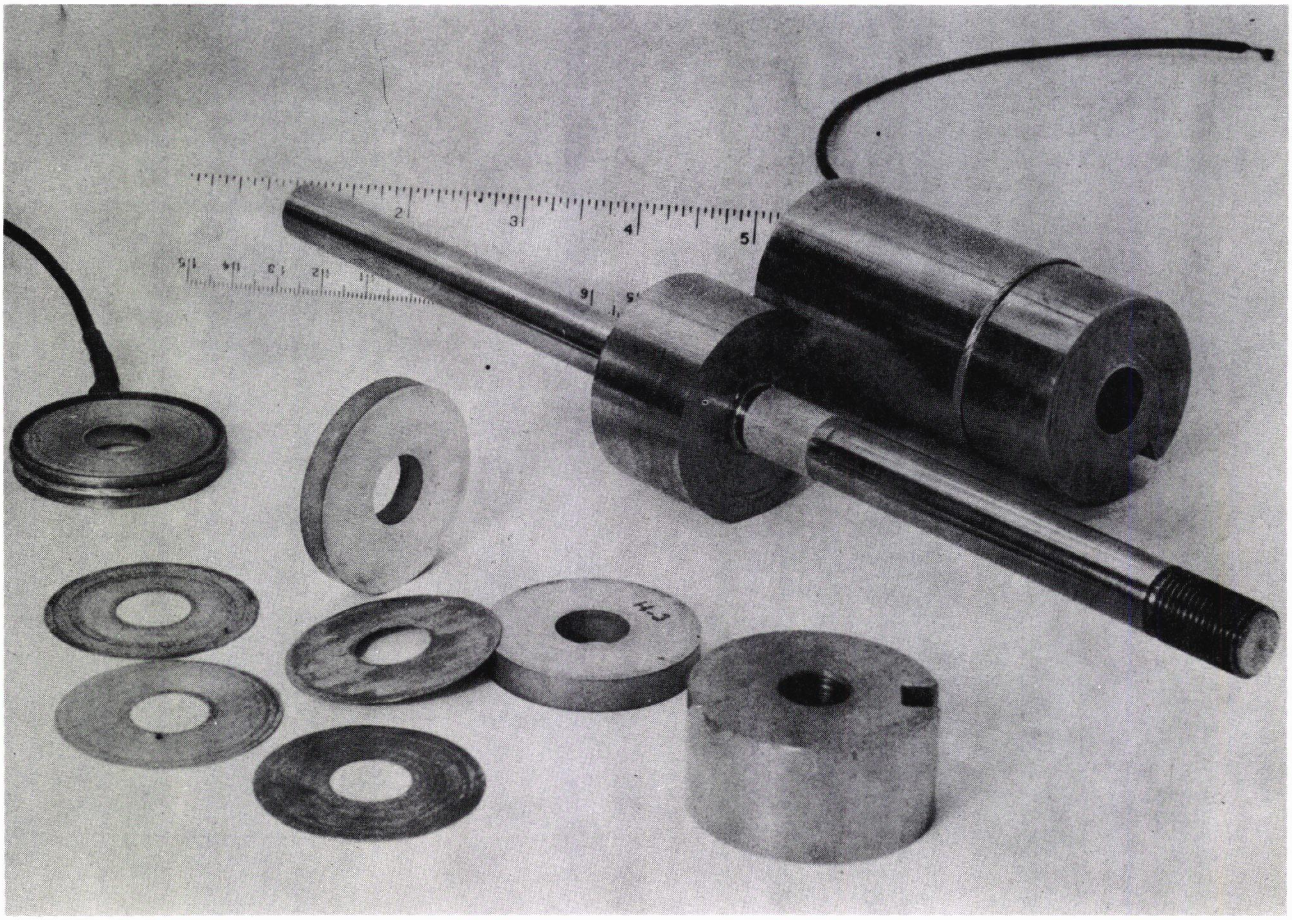

Figure 1. Piezoelectric transducer Model P-7-A.

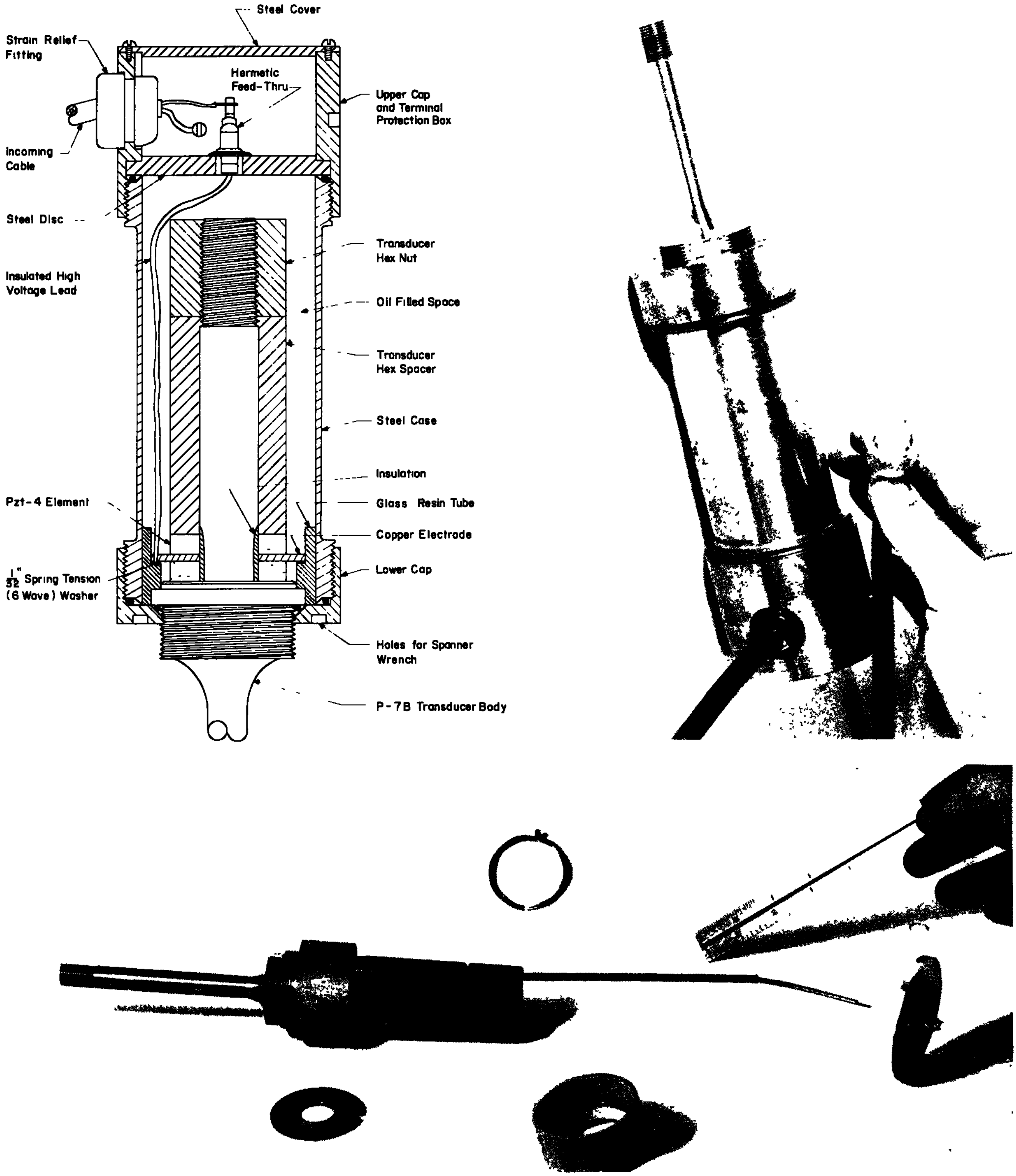

Figure 2. Components of P-7-B piezoelectric transducer showing (upper left) cross section and (upper right) electrical connecting devices and protective sleeve.

structed to produce 6,800 lb of impact at 8,000 vibrations per minute. Because the weight of the whole assembly is usually 100 lb or less, the output forces of this type of transducer are quite large in comparison to size and weight.

Performance Characteristics

Commercially available vibration inducers cover a wide range of frequencies and amplitudes. The rotating-ball type can be purchased in a range of frequencies from 8,500

to as low as 1,500 vibrations per minute (143 to 25 cps). This frequency range can be combined with force amplitudes varying from a few ounces to slightly over 6,000 lb impact. Transducers of the rotating-mass type range in frequency from 500 to 8,000 vpm (8 to 134 cps) and provide impact forces of 375 to 6,800 lb. With this wide range of combinations, many possible highway applications can be visualized.

PIEZOELECTRIC TRANSDUCERS

Development of piezoelectric transducers has been undertaken on a related project simultaneously with this investigation. Novel basic designs have been developed into rugged transducer systems providing outputs approaching 1 hp per cubic inch, with operating efficiencies of 90%. These transducer designs involve piezoelectric ceramics (lead-zirconate-titanate) operating under static compression loads (to prevent ceramic cracking under tension). The piezoelectric elements are located near the nodes of the horn assemblies. Steel structures, integrated with the motor elements, provide vibration amplification at the output ends of these transducer systems. Small transducers of this design, operating at ⅓ to ½ hp at 10-kcps frequency, have been made available for use during the present investigation.

P-7 Type Piezoelectric Transducers

Figure 1 shows a typical example of the smaller piezoelectric transducer. The basic structure consists of a central steel shaft with an enlarged center section, on which all other components are assembled. The piezoelectric elements, in the shape of washer-like discs, form a sandwich containing the copper electrode. The large-diameter collar and retaining nut complete the assembly of the large-diameter portion of the transducer. The small-diameter extension of the central member on the opposite end provides the necessary vibration amplifier. The vibratory power output is taken from the end of the small-diameter member of the assembly.

Electrical insulation is provided by means of concentric layers of insulating material around the central shaft within the transducer section. External leads are connected to the copper electrode between the piezoelectric discs by means of an electrode ring and wave washers which isolate vibrations from the external electrical connections. This design has permitted continuous operation over extended periods without component failures.

Complete enclosures have been designed for the P-7 type transducers (Fig. 2). These provide protection from the high-voltage excitation circuits and permit mounting of the encapsulated transducer assemblies on fixtures (such as small drill presses).

Over-all efficiency of the P-7 type transducer has been measured by means of "motor-generator" tests, in which two identical P-7 transducers are coupled by nuts at the output ends (small-diameter shafts). One of the units then serves as a "motor," converting input electrical energy into mechanical vibrations that pass longitudinally along the small-diameter shaft and coupling to the second unit. The second unit then performs as an electrical generator, transforming the mechanical vibrational energy back into electrical energy. This output energy is used to light a number of incandescent lamp bulbs in series (Fig. 3), to dissipate the energy. High-frequency wattmeters in both input and output circuits are used to measure power levels and to permit computation of over-all efficiencies. Typical performance involves transmission of 350 w, with 84% over-all efficiency. Inasmuch as two identical units are involved, the apparent power efficiency of each P-7 transducer is found to be nearly 91%.

Units of the P-7 design were available during the latter portions of the present investigation, and were used in preliminary evaluations of sonic compaction of soils and bituminous materials, as described elsewhere in this report. However, in most cases it is difficult to attain full power output into mechanical loads such as soils, because power transfer depends on the static loads (surcharge) applied, the acoustic efficiency of coupling systems, and the impedance mismatch conditions at the compactor-soil interface.

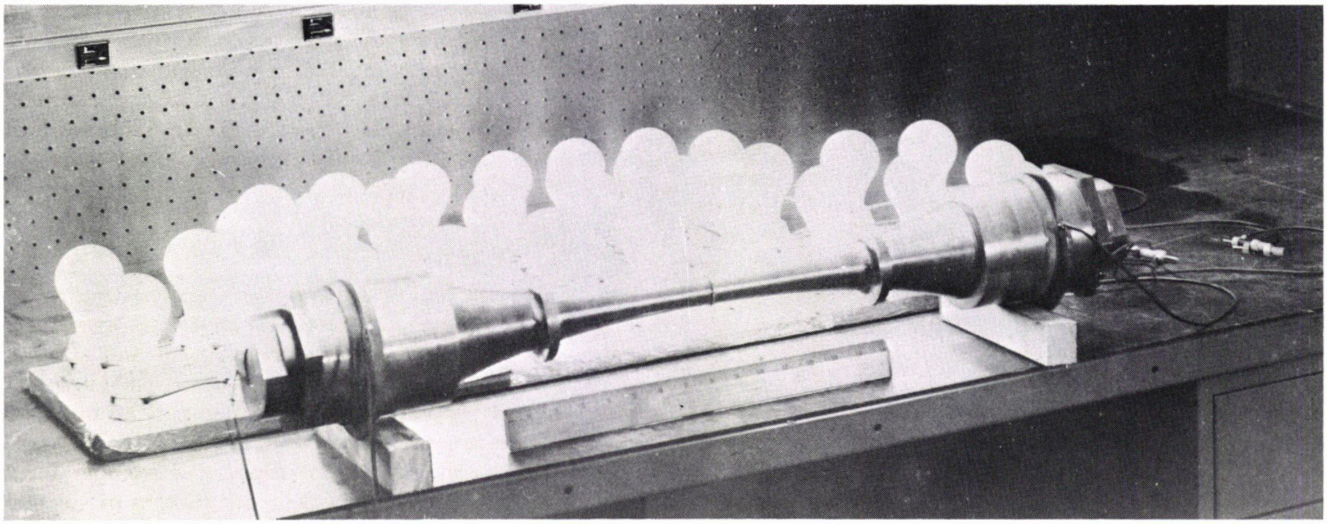

Figure 3. Typical design of more recent P-7 transducers. Here two units are coupled together to demonstrate efficiency of the units by converting vibrations of one back to electrical energy in the second.

Because technologies for attaining optimum conditions at these points are as yet undetermined, it must be concluded that test results to date are not necessarily optimum for sonic compaction at frequencies of 10 kcps, and that further tests would be desirable.

Larger Piezoelectric Transducers

Since the completion of experimental work on the present investigation, work on the related project has resulted in development of piezoelectric transducers with power output in the range of 5 hp. Typical units are shown in Figure 3. With the greatly increased vibratory power outputs possible with these enlarged piezoelectric transducers, much improved performance in compaction, and much higher surcharge loads, may be feasible. Piezoelectric transducers with power outputs adequate for more significant evaluations of sonic compaction systems are presently under development; therefore, it can be recommended that further studies of compaction would be desirable at these much-enhanced vibratory power levels.

CHAPTER THREE

DESIGN OF EXPERIMENT

The main structural elements involved in highway construction are (a) the embankment, (b) the foundation, (c) the cut, and (d) the pavement. The factors which should be considered in design and construction of these elements are generally divided into (a) structural problems and (b) construction problems.

Structural Problems

A highway embankment, if properly designed and constructed, should possess stable slopes and should not settle to any great extent. The settlement generally results from (a) further compaction of embankment material due to the weight of the pavement and the action of traffic and (b) further compaction and consolidation of the foundation. Large differential settlement may occur over a short distance and cause structural damage to the highway. Wherever improper compaction occurs, especially at bridge abutments or where there is a sudden change in the thickness of fill, such differential settlement is liable to occur.

Embankments require a stable foundation in the same way as other structures. The foundation material has to be treated in such a way that no excessive settlement occurs in the embankment. The densification characteristic and the bearing capacity of the foundation soil are of importance in the design of highways; for example, swelling of the floor of a cut is generally noticed in highly compressible soils where, due to removal of part of the overburden pressure, the soil swells and causes undesirable stresses in the pavements.

The flexible highway pavement consists of subgrade, subbase, base, and surface courses. The structural problems for pavement can generally be classified as (a) those related to the action of traffic and (b) those due to the effect of weather. The principal way in which traffic causes a loss of pavement support is thought to be by the compaction of the material. This may take the form of a local reduction in volume of the subgrade soil, which results in differential settlement of the highway. Further compaction in base may cause excessive degradation of mineral aggregate, which may in turn result in a frost-susceptible material. Excessive densification in the surface layer may cause failure in the asphaltic layer by reducing its voids to nil and thus squeezing the binding agent to the surface.

Construction Problems

The principal problems involved in the construction of road embankments are the choice of the material and its compaction into a dense, stable mass. Adequate compaction of the material reduces settlement, increases the stability of the slopes, and reduces the tendency of the material to absorb water.

Construction problems in foundation and cut involve, primarily, identification of the material and a knowledge of its behavior in loaded and unloaded conditions. In some cases, of course, it would be more economical to replace a foundation soil with one of known behavior.

Pavement construction problems deal with providing adequate resistance to the action of traffic and weather. In general, the requirements are (a) to obtain adequate compaction of the soil, (b) to maintain the subgrade in a stable condition at a constant moisture content, and (c) to protect the subgrade from frost.

COMPACTION

The performance of highways under traffic depends as much on the supporting characteristics of the foundation and embankment soils as does the strength and stability of buildings and bridges. In the case of buildings and bridges added supporting strength often can be obtained by deepening the foundation. In the case of highways this is not possible; additional supporting strength must come from the selection and the reconstitution of suitable layers of materials placed between the natural soil and the traveled surface. Most soils can be brought up to the required strength by mechanical compaction. In fact, com-

paction probably ranks second only to drainage in importance among all the factors which influence pavement performance with respect to riding qualities and pavement life. Compaction is defined as the process whereby soil particles are constrained to pack more closely together through a reduction in air voids, generally by mechanical means. Compaction is measured quantitatively in terms of the density (for soils, dry density) of the material. Type of material, amount of compaction, and method of compaction have great effect on the behavior of highway components under the action of traffic and weather.

Although the compaction of soil to a density sufficient to insure stability of highways under heavy loads can be successfully accomplished by the use of heavy rolling equipment on thin layers of soil, the development of a compaction procedure which will involve lighter equipment and thicker layers of soil is greatly to be desired.

The possibility of utilizing vibratory forces in the compaction of soil has been realized, and several attempts have been made to design vibration compaction equipment. In general, these attempts have met with only limited success, due largely to a lack of knowledge of the basic laws governing compaction of soils by vibration.

It was these thoughts and the problem outlined that led to the selection of compaction characteristics of highway material as a potential area for application of sonic and ultrasonic devices.

Basic Concepts Underlying Soil Compaction

The density of a soil is determined by its specific gravity and the quantity of voids present. If there is no deformation in the particles (no change in specific gravity of the soil), the only way to increase the density is by relocation of the particles or by filling the voids with more soil. The size of the soil particles used to fill the voids must be small enough compared to the size of the present particles so that the apparent volume of the packing will not be increased. The particles when relocated and shifted around generally cause a change in density. For spherical particles of equal diameter, it is found that the voids ratio varies from 0.26 to 0.48 depending on whether the particles are arranged in rhombohedral (closest) packing or cubic (loosest) packing. Of course, for an arrangement of sized particles, almost any degree of porosity is possible. The relocation can best be achieved when the particles are subjected not only to a vertical but also to a horizontal motion.

In practice, when a soil is subjected to densification the composition, size distribution, and shape of its particles are unchanged, assuming no degradation occurs during the densification process. Hence, any further densification would be due to relocation of its particles. The nature of this relocation and its effect on the soil density depend on friction, cohesion, water content, and applied load.

The particles under load, whether static or dynamic, may deform elastically or plastically, or relocate. The general contribution of elastic and plastic deformations of particles to densification of soil is negligible. The relocation under static load is retarded by friction between individual particles which may produce a certain self-locking effect. Dynamic load, however, causes a great reduction of friction if it induces relative motion between particles.

Cohesive and Noncohesive Soils

Soils in general can be divided into cohesive and noncohesive types. The load-supporting characteristic of noncohesive soil is largely due to friction and interlocking of its particles, whereas that of cohesive soil is mostly due to attractive and repulsive forces which exist between particles. The densification of noncohesive soils is mostly a matter of overcoming the interparticle friction and forcing the particles to attain a more stable position. Free water acting as a quasi-lubricant will further assist as a friction reducer.

For noncohesive soils, static loads produce almost no relocation effects; hence, the depth of densification cannot be large. This is due to the fact that the horizontal force component cannot be larger than the force due to the contact friction. Vibration, however, may cause the individual soil particles to move with displacement and acceleration amplitudes of various magnitudes. Hence, the friction of rest between the particles is transformed into the smaller friction of motion. In this case, relocation will be facilitated, giving the smaller particles an opportunity to move into the voids between the larger particles.

Conditions are more complicated for cohesive soils. It is generally understood that a knowledge of soil structure is necessary in order to explain the behavior of a cohesive soil under compaction. The soil structure, in broad terms, is defined as the particle or aggregational arrangement plus any forces inherently pulling and holding the solids together. For example, it is the combination of soil structure and the effects of any applied external pressure which produces soil strength.

In noncohesive soils, such as clean sands and gravels, there is a simple bulky-grained structure which must be held together by confining pressure in order for the soil to have any significant strength. In cohesive soils (clayey materials) electrical forces of attraction and repulsion are of considerable importance in determining the soil behavior. These forces are large in proportion to gravity forces in clays, because the particle surface area over which the former act are larger in comparison to the mass. The need for a structural concept to explain the change that may occur in soil with time and pressure is obvious. Compaction will change the structure, which in turn causes a change in soil properties.

Clay-Water Systems

In a clay-water system, the particles are of colloidal size, carry a negative charge, and are surrounded by an ionic swarm. The water close to a particle surface is ionized and is generally referred to as a double layer. When double layers of two particles overlie, there is natural repulsion, and as the particles move closer together, the repulsion increases. Particles may move closer together to satisfy intermolecular forces of attraction (Van der Waal forces) or through the application of an external pressure.

In a colloidal suspension (saturated clay) particles may approach each other and, under the influence of net attrac-

tive force, join or flocculate into aggregates of particles. If the repulsion forces predominate, the particles are dispersed in the suspension. The flocculation is not generally face-to-face, producing a rather open, low-density sediment. Pressure applied subsequently tends to push the particles into a more parallel or oriented structure, but the interparticle forces must be overcome to accomplish such a structural change. The sediment from a dispersed suspension is initially one which is well oriented. Subsequent pressure on this structure improves the orientation somewhat, but largely is available for decreasing the particle spacing.

Probably the double-layer water can be squeezed out by pressure down to the adsorbed layer, but in general there is only an effective contact between the particles through the adsorbed or double-layer water. This held water has properties significantly different from bulk or free water. For example, it has a low freezing point, it has high viscosity, and remarkably, due to a nonoptimal structure of the water, is of lesser density than bulk water. Oven drying to 105 C removes some to all of the adsorbed water.

The clay particles can be moved closer together by an increase in confining pressure or in attractive pressure; to accommodate this movement, the double layer must be reduced in thickness. Compression is accomplished by moving the particles closer together and/or moving the particles into a more oriented structure. In expansion or rebound some of the particle spacing change is recovered, but the volume change that was accomplished by orientation of particles is not recovered.

Forces of Attraction and Repulsion of Particles

It is possible to calculate the attractive and repulsive forces only under rather idealized conditions. In lieu of looking directly at the basic forces responsible for strength, the following related factors are examined:

1. *Particle spacing.* All other things being equal, the closer the particles, the greater the strength. This is verified by experience.

2. *Particle orientation.* For a given average particle spacing, the more oriented the particles, the less the shearing resistance. Due to the exponential nature of the attractive forces, there is greater gain in attraction at the close end in the nonoriented structure than there is loss in attraction at the far end. In other words, at a given density a soil sample with flocculent structure is stronger than one with an oriented structure. Factors 1 and 2 often work in opposition, inasmuch as natural materials with a highly flocculent structure commonly exist at a large average particle spacing (low density).

3. *Applied stress.* Such stress can change particle spacing and/or orientation. Applied stress with poor drainage condition may temporarily reduce strength through mobilization of pore pressure and reduction in effective stress. In other cases, applied stress produces negative pore pressure and higher effective stress. The increase in strength with increase in applied stress is well documented by experience.

VIBRATORY COMPACTION

Compaction is an energy-consuming process which results from the application of forces to the material. The material —soil, fresh concrete, or bituminous mixtures—withstands these forces in many ways, such as by interlock, by frictional resistance, and by viscous or flow resistance. When the applied forces have a greater component in any direction than the resistance of the material, the material will move and shift around until a more stable position is attained, or until a confining position is reached, or until the force is removed. This rearrangement of the material, especially in granular material, causes a closer packing of particles, a new internal arrangement or structure, and a higher unit weight.

The three most important modes of transferring energy to a highway material for its compaction are (a) static (rolling), (b) ramming, and (c) vibration. Vibrational energy under high frequencies, or sonic energy, at present is not fully utilized for the compaction of highway material simply because adequate power levels of sonic, especially ultrasonic, vibrations are not available. The energy input required for compaction of any highway material is much larger than ultrasonic energy which can be produced on a commercial scale. Negligence in recognition of the validity of the law of conservation of energy has led to many unsuccessful experimentations in this field.

Vibratory or Sonic Power

Sonic power levels are a function of (a) sonic force levels, (b) displacement amplitudes, and (c) operating frequencies. A careful selection of the optimum ranges of these factors for each application would always result in maximum beneficial effects for the minimum sonic power requirements. Basic to an understanding of sonic power levels and effects of variations in magnitudes of forces, displacements, and frequencies is the relationship between displacement, velocity, and acceleration with sinusoidal oscillators.

Sinusoidal oscillations at a single frequency can be described mathematically in terms of maximum displacement amplitudes and instantaneous displacement by

$$s = S \sin \omega t \qquad (1)$$

where

t = time, in seconds;
$\omega = 2 \pi f$ (angular velocity), in radians per second;
f = vibration frequency, in cycles per second;
s = instantaneous displacement, in meters or feet; and
S = peak displacement, in meters or feet.

The corresponding velocity and acceleration of the face of the vibrating transducer are given by the first and the second time derivatives of the displacement, or

$$v = V \sin (\omega t + 90°) \qquad (2)$$

$$a = A \sin (\omega t + 180°) \qquad (3)$$

where

$V = \omega S = 2 \pi f S$ = peak velocity; and
$A = \omega^2 S = 4 \pi^2 f^2 S$ = peak acceleration.

From Eqs. 2 and 3 it is apparent that the peak velocity and peak acceleration of a transducer face, vibrating with constant amplitude, are proportional to the frequency of vibration and the square of the frequency of vibration, respectively. Also it is evident that the velocity wave leads the displacement wave by 90°, but the acceleration is in phase opposition to the displacement vibration.

Response of Soils to Vibratory Loading

Due to lack of sufficient knowledge of response of soils to dynamic loading, and due to mathematical complication in treating the response of soils to vibration theoretically, the response of some simple idealized media to vibration is generally treated mathematically. These mathematical derivations are then used in some modified form to explain the response of a true material to vibration. The three most commonly used idealized media are (a) lumped linear elastic medium, (b) Newtonian viscous medium, and (c) a rigid mass or inertial medium. In practice, obviously, purely elastic, viscous, or inertial media are rarely encountered. As the first approximation, it is generally assumed that soils can be represented by linear combinations of all three idealized media. Similar assumptions are made in static analysis of soil response to various kinds of loading. In static analyses it is often assumed that the response of soils can be approximated as the response of a linear viscoelastic material. The relation between stress and strain for such a material is generally shown in the differential form

$$P(\xi) = Q(\epsilon) \tag{4}$$

where ξ is a stress component, ϵ is a related strain component, and, in terms of the differential operator $D = \frac{\partial}{\partial t}$,

$$P = \sum_{r=0}^{n_p} p_r D^r \text{ and } Q = \sum_{r=0}^{n_q} q_r D^r,$$

p_r and q_r are material constants, and n_p and n_q are positive integers not necessarily equal. The major difference between viscoelastic materials and purely elastic materials is the time dependency of the former. It is this property which makes it more appropriate when dealing with soils and bituminous mixtures to give primary consideration to the nonlinear viscoelastic properties rather than the linear elastic properties. This is more so in cases where long-range behavior of soils and other materials is of interest, such as consolidation characteristics of saturated soils and creep and relaxation behavior of asphaltic mixtures. In vibrational analysis with a high frequency of load application, the inertia effect must be added to the load-deformation relationship of viscoelastic materials.

Solutions to Eq. 4 generally require some simplification. This is usually achieved by solving Eq. 4 for low-order operators p and q, which correspond to simple materials such as a Maxwell liquid or a Kelvin solid. Electrical and/or mechanical analogies are developed for load response of viscoelastic materials. In mechanical analogy, by coupling simple mechanical elements in various forms, differential equations similar to Eq. 4 can be developed. Basic elements in a mechanical analogy consist of spring, dashpot, and lumped mass (for dynamic case). The response of these simple elements to loading is assumed to be such that simple mathematical expressions exist for their stress-strain or load-displacement relations, as follows:

$$\text{For spring} \quad F = K_s S \tag{5a}$$

$$\text{For dashpot} \quad F = K_f D S \tag{5b}$$

$$\text{For lumped mass} \quad F = K_v D^2 S \tag{5c}$$

where

F = applied force;
S = displacement;
K_s = spring constant, or elastance;
K_f = dashpot constant, or coefficient of viscous friction;
K_v = mass constant, or inertance; and
$D = \frac{\partial}{\partial t}$

Coupling of these elements in series or parallel results in various forms of Eq. 4. The response of soils and bituminous mixtures to loading in some cases can be approximated by combination of an infinite number of these elements in parallel and/or in series. It is shown, except in special cases, that the response of soils cannot be approximated by linear models and nonlinear viscoelastic models must be used. However, due to mathematical complications, linear viscoelasticity in some cases, and linear elasticity in most cases, are the two major methods of analysis.

Behavior of Linear Viscoelastic Materials Under Vibration

When a transducer system producing a sinusoidal oscillation at a single frequency is connected properly to an ideal spring, dashpot, or lumped mass, the forces required for vibration of each element can be determined from Eqs. 5; that is,
for a spring or lumped elastic medium

$$F_{\text{elastic}} = K_s s \tag{6}$$

for a dashpot or viscous medium

$$F_{\text{viscous}} = K_f v \tag{7}$$

and for a lumped mass

$$F_{\text{inertial}} = K_v a \tag{8}$$

where

s = instantaneous displacement;
v = instantaneous velocity of viscous friction member; and
a = instantaneous acceleration.

For such a transducer, Eqs. 1, 2, and 3 give the relationships between displacement s, velocity v, and acceleration a, and the frequency of vibrations. Substitution of Eqs. 1, 2, and 3 in Eqs. 6, 7, and 8 gives

$$F_{\text{elastic}} = K_s S \sin \omega t \tag{9}$$

$$F_{\text{viscous}} = K_f V \sin (\omega t + 90°) \tag{10}$$

$$F_{\text{inertial}} = K_v A \sin (\omega t + 180°) \tag{11}$$

Eqs. 9, 10, and 11 show that maximum force required to vibrate a medium depends on the force-displacement characteristic of the medium. For a weightless linear elastic material

$$\text{Max } F_{\text{elastic}} = K_s\, S \tag{12}$$

which shows that for such a material the maximum force is not a function of frequency and has an amplitude directly proportional to the maximum displacement, S.

For a viscous medium the maximum force would be

$$\text{Max } F_{\text{viscous}} = K_f\, V = 2\, \pi\, f\, K_f\, S \tag{13}$$

From this relation it is apparent that maximum viscous force for a given displacement amplitude is directly related to frequency.

Finally, for a lumped mass

$$\text{Max } F_{\text{inertial}} = -\, K_v\, A = 4\, \pi^2\, f^2\, K_v\, S \tag{14}$$

which shows that vibration of a lumped mass at high frequencies requires enormous maximum force, because maximum force is directly related to the square of frequency of vibration.

For a material whose load response can be approximated by a combination of a spring, a dashpot, and a mass connected in series, McMaster et al. (*1*) show that the forces due to each type of load would be vectorially additive; that is,

$$\begin{aligned} \overline{F}_{\text{total}} &= \overline{F}_{\text{elastic}} + \overline{F}_{\text{viscous}} + \overline{F}_{\text{inertial}} \\ F_{\text{inst}} &= K_s\, S \sin \omega t + K_f\, V \sin (\omega t + 90°) + \\ &\quad K_v\, A \sin (\omega t + 180°) \\ &= S\, [K_s \sin \omega t + K_f\, (2\, \pi\, f) \sin (\omega t + 90°) + \\ &\quad K_v\, (4\, \pi^2\, f^2) \sin (\omega t + 180°)] \end{aligned} \tag{15}$$

From this relation, they conclude as follows:

1. Each force component increases directly in proportion with maximum vibration amplitude, S.
2. The peak elastic force component, $F_{\text{elastic}} = K_s\, S$, is independent of frequency, and may predominate at very low frequencies or with static loading. This force is in phase with the displacement, S.
3. The peak viscous-friction force component, $F_{\text{viscous}} = 2\, \pi\, f\, K_f\, S$, varies directly with frequency and (in the absence of large inertial elements) may predominate at intermediate and higher frequencies. This force leads the displacement, s, by 90°.
4. The peak inertial force component, $F_{\text{inertial}} = 4\, \pi^2\, f^2\, K_v\, S$, can increase with enormous rapidity at higher frequencies, and may predominate at all except the lowest frequencies. This force is in phase opposition to the elastic force component.
5. At resonance within the driven load (medium) the elastic forces and the inertial forces (which are in phase opposition) may cancel each other, permitting vibration at the peak amplitude permitted by the viscous-friction force component. At resonance in such a system the total force is in phase with the vibration velocity, v.
6. As frequency varies, such a combined system changes its apparent characteristics, its vibration amplitudes, and its force levels, in accordance with the vector summation of the component forces.

Natural materials can be approximated more realistically by more complex connections of the three simple elements. Complex connections would result in more complex analysis, but the influences of different basic types of material are similar. This shows that the nature of a highway material would control the selection of the appropriate force, displacement, and frequency levels of a transducer used for its compaction. Therefore, if, due to its characteristics or limitations, a transducer cannot provide the desired levels of force, frequency, and displacement, its use for compaction of that material would not render satisfactory results.

Energy Transferred from Transducer to Material

In order for a material to be subjected to vibration, energy or power (work per unit time) must be transferred from the transducer to the material. This transfer of power depends, of course, on the type of connection that exists between the vibrator and the material. For compaction the vibrator generally is coupled to the material only for a part of the displacement stroke. In this case the energy delivered for compaction by each stroke is given (*1*) by

$$W = \int_t^{t+\delta t} F\, v\, dt = \int_s^{s+\delta s} F\, ds \tag{16}$$

where the integral is taken over the time interval, δt, or over the range of displacement, δs, that the vibrator is in contact with the material. Therefore, it is evident that one way to increase the energy transferred from the vibrator to the material would be to increase the contact time, δt, per stroke. This can be achieved by application of static load simultaneously with the dynamic load of the transducer. This static load is generally referred to as ballast load or surcharge load. The minimum weight of the ballast load required to prevent the vibrator from jumping out of contact with the work material during the period that the alternating force is acting in an upward direction is equal to the maximum force amplitude of the vibrator. For example, for a vibrator which has a maximum amplitude of 20,000 newtons (the unit of force), a ballast load of at least $20{,}000 \times 0.102 = 2{,}040$ kg (unit of mass) is needed to prevent upward movement of the vibrator.

When the connection between the transducer and the vibrating material is continuous, simple relations exist between power input and force and velocity.

$$P = F\, v = F\, V \sin (\omega t + 90°) = F\, V \cos \omega t \tag{17}$$

where

P = vibratory power transferred;
F = instantaneous force; and
$v = V \cos \omega t$ = instantaneous velocity.

Because the force is itself a sinusoidal oscillation such that

$$F = F_{\max} \sin (\omega t \pm \theta)$$

where θ is the phase angle between displacement and force, it can be shown (*1*) that the instantaneous power transferred is

$$P = \tfrac{1}{2}\, F_{\max}\, V\, [\sin \theta + \sin (2\, \omega t \pm \theta)] \tag{18}$$

TABLE 1

TRANSFERRED POWER TO THREE IDEAL MATERIALS

	POWER TRANSFERRED		
FORCE COMPONENT	ELASTIC MATERIAL	VISCOUS MATERIAL	INERTIAL MATERIAL
P_{avg}	0	$2\pi^2 K_f f^2 S^2$	0
$P_{max\ oscillating}$	$\pi K_s f S^2$	0	$-4\pi^3 K_v f^3 S^2$

It is further shown (*1*) that this mechanical power can be divided into an average mechanical power and an oscillating (double-frequency) component such that:

$$P_{avg} = \tfrac{1}{2} F_{max} V_{max} \sin\theta \tag{19}$$

and

$$P_{oscillating} = \tfrac{1}{2} F_{max} V_{max} \sin(2\omega t + \theta) \tag{20}$$

McMaster et al. (*1*) have shown that due to different force requirements of the three basic elements—elastic, viscous, and inertial—the transferred power from a transducer to them would be different. Table 1, giving P_{avg} and $P_{oscillating}$ components of a transferred power to the three basic elements, shows that the average power transferred to elastic materials over any whole number of cycles of vibration is equal to zero. The oscillating power for such a material would be proportional to frequency and to the square of the amplitude. This power may be used to displace the material.

In viscous materials, in contrast to elastic media, there is no oscillating component of the force, thus the power flows from transducer to the material only. It is evident that, at high frequencies, very high transferred powers are required to overcome the viscosity of the material. This is due to dependency of the transferred power on the square of the frequency. This high power demand becomes more critical in inertial-type materials where, according to Table 1, the oscillating power is directly related to the cube of the frequency and the square of the amplitude. This power requirement is the main reason for use of very low audio frequencies for compaction purposes.

In natural materials, elastic, viscous friction, and inertial components are often present. For a simple case when these components can be assumed linear and connected in series, it can be shown that the average power input would be equal to that for the viscous friction component only, because the average power received by the elastic and inertial components is exactly zero; that is,

$$P_{avg} = \tfrac{1}{2} F_{max} V_{max} = 2\pi^2 K_f f^2 S^2 \tag{21}$$

However, the oscillating double-frequency power transferred would be

$$P_{max\ oscillating} = (\pi K_s - 4\pi^3 K_v f^2)(f S^2) \tag{22}$$

This shows that at low frequencies the transferred power is primarily controlled by the elastic behavior of the material, whereas at intermediate and high frequencies the mass of vibrating material would control the magnitude of the oscillating power.

For viscous materials without any elastic component, $K_s = 0$, and the ratio of average power to oscillatory power would be

$$\frac{P_{avg}}{P_{oscillating}} = \frac{2\pi^2 K_f f^2 S^2}{4\pi^3 K_v f^3 S^2} = \frac{1}{2\pi f}\left(\frac{K_f}{K_v}\right) \tag{23}$$

This ratio is maximized by reduction of frequency, f, to a practical minimum. This again shows that at lower frequencies more power will be used to overcome frictional resistance of the vibrating material.

Oscillatory Force

The behavior of a model consisting of a mass M, a spring with constant K_s, and a dashpot with constant K_f, with one degree of freedom as shown in Figure 4 and subject to an oscillating force of

$$F = \hat{F} \sin\omega t \tag{24}$$

is used by many investigators as that representative of soils. The governing differential equation of motion for such a model is

$$M D^2 s + K_f D s + K_s s = \hat{F} \tag{25}$$

Now let

$$s = a \sin(\omega t - \phi) \tag{26}$$

where

$$a = \frac{F}{(\omega^2 M - K_s)^2 + (K_f \omega)^2} \tag{27}$$

The amplitude of force is proportional to the square of the frequency, or

$$\hat{F} = C\omega^2 \tag{28}$$

where C is a constant.

Resonance in an undamped system occurs for

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K_s}{M}} \tag{29}$$

where

f_r = undamped natural frequency, in cps; and
$2\pi f_r = \omega_r$.

The resonant frequency for maximum displacement can be obtained by maximizing Eq. 27. Substitution of the resonant frequency and Eq. 28 in Eq. 27 results in

$$a_r = \frac{C\omega_r}{K_f} \tag{30}$$

where

a_r = displacement amplitude at resonance; and
ω_r = angular velocity at resonance.

After some manipulation it can be shown that

$$\frac{a}{a_r} = \frac{\omega/\omega_r}{\sqrt{1 + \frac{K_s}{\omega_r^2 K_f}\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)^2}} \tag{31}$$

By using a dimensionless quantity for the amplitude, van der Poel (2) has shown that

$$\xi = \frac{\omega^2/\omega_r^2}{\sqrt{\frac{1}{Q^2}\frac{\omega^2}{\omega_r^2} + \left(-\frac{\omega^2}{\omega_r^2} + 1\right)^2}} \qquad (32)$$

where

$\xi = a\, K_s\, M$ a dimensionless quantity; and

$Q = \frac{K_s}{K_f\, \omega_r}$

Eq. 32 shows that for fixed values of Q, and at low frequencies, ξ (a measure of displacement) increases rapidly with frequency. This indicates that at low frequencies the generated force has only to overcome the resistance of the elastic component. At higher frequencies, however, the inertia of the mass M makes itself felt and resonance phenomena occur. The displacement finally reaches a constant value independent of frequency. This point can also be shown mathematically. At frequencies far above resonance, the following can be derived from Eq. 27:

$$a_\infty = \frac{F}{\omega^2 M} \qquad (33)$$

Using Eq. 30, this becomes

$$a_\infty = C/M \qquad (34)$$

where

a_∞ = displacement amplitude at frequencies far above resonance;

C = a constant, same as in Eq. 28; and

M = the lumped mass.

Eq. 34 clearly shows that, at high frequencies, the amplitude of displacement is independent of the frequency.

If the derived theoretical expression for displacement amplitude (Eq. 32) gives results comparable to the experimental values, it may be concluded that the original assumption of a one-degree-of-freedom system with viscous damping describes the behavior of soils accurately enough. However, Bernhard and Finelli (3), from extensive laboratory and field experimentation, concluded ". . . a comparison between a vibrator-soil system and a linear mass-spring system is not accurate enough, or at least not better than a first-order approximation." They further concluded that ". . . a soil mass-vibrator system is of a rather complex nature and requires a basically different analytic approach."

Consideration of the problem of vibrations of an elastic medium provides insight into the problem of vibration of soils. A solution of this problem is given by Reissner (4).

The differential equation governing the vibration in a semi-infinite elastic solid, induced by a force, $P \sin(\omega t)$, which harmonically changes with time, can be written

$$m\ddot{z} + R \exp(i\,\omega t) = P \exp[i(\omega t + \epsilon)] \qquad (35)$$

where

R = magnitude of soil reaction against vibrator;

ϵ = phase shift between exciting force and soil reaction;

z = vertical displacement;

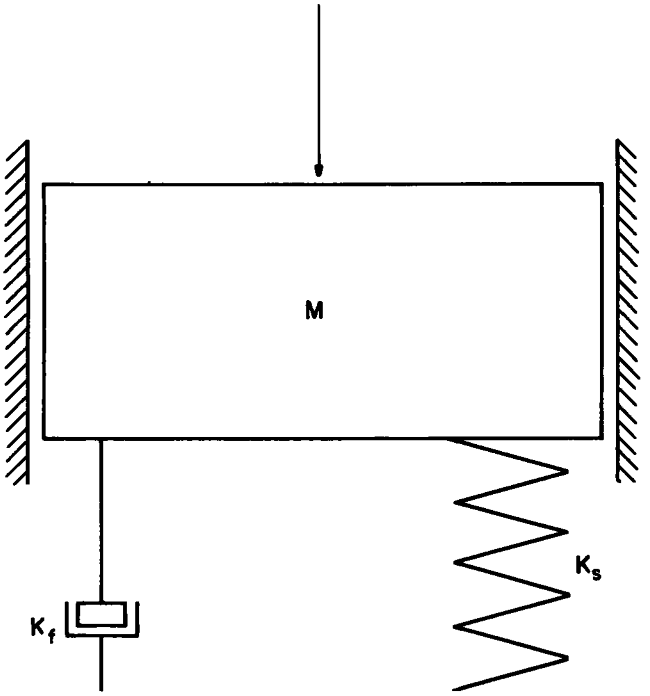

Figure 4. Schematic representation of a linear, lumped parameter, single degree of freedom vibratory system with viscous damping.

ω = frequency of vibrator; and

m = mass of vibrator.

For values of R, Reissner used the magnitude of the settlement of the soil under the center of a uniformly loaded absolutely flexible circular area. After complicated mathematical derivations, he found the following simple relationship between R and Z:

$$Z = -\frac{R}{r_0 G}(f_1 + i f_2) \exp(i\,\omega t) \qquad (36)$$

where

G = shear modulus of elasticity of soil;

r_0 = radius of a circle = $\sqrt{A/\pi}$;

A = contact area between transducer and soil; and

f_1 and f_2 = functions depending on the ratio between the radius r_0 of the circle and the length of the shear waves propagated by the vibrator in the soil, and also depending on Poisson's ratio of soil.

Barkan (5), by substituting Eq. 36 in Eq. 35, determined the equations for R and $\tan\epsilon$. Substituting the expression for R and $\tan\epsilon$ in Eq. 36 and neglecting the imaginary part, he obtained the following for the amplitude of vibration:

$$a = \frac{P}{G r_0}\sqrt{\frac{f_1^2 + f_2^2}{[1 + (m\,\omega^2/G\,r_0)\,f_1]^2 + [(m\,\omega^2/G\,r_0)\,f_2]^2}} \qquad (37)$$

The following expressions are also given by Barkan and Reissner for phase shift, ϕ, between the exciting force P and the displacement Z, and the amount of energy L that is required to maintain the vibration (the power requirement):

$$\tan \phi = -\frac{f_2}{f_1 + (m\,\omega^2/G\,r_0)\,(f_1^2 + f_2^2)} \tag{38}$$

and

$$L = -\frac{P^2\,\omega\,f_2}{2G\,r_0\left[\left(1 + \frac{m\,\omega^2}{G\,r_0}\,f_1\right)^2 + \left(\frac{m\,\omega^2}{G\,r_0}\,f_2\right)^2\right]} \tag{39}$$

where

$\phi = \alpha + \epsilon$; and

$\tan \alpha = -f_1/f_2$, the phase shift between displacement and the reaction of the soil.

By introducing a dimensionless value, b,

$$b = \frac{m}{\gamma\,r_0^3} \tag{40}$$

where γ is the soil density,

$$\frac{m\,\omega^2}{G\,r_0} = b\,\chi^2 \tag{41}$$

where

$$\chi = \frac{2\,\pi\,r_0}{L_s};\ \text{and} \tag{42}$$

L_s = length of shear waves propagated in the soil

$$= 2\,\pi\,V_s/\omega \tag{43}$$

where V_s is the velocity of the shear wave in the soil.

Appropriate substitutions in Eqs. 37, 38, and 39 give

$$\frac{a\,G\,r_0}{P} = \sqrt{\frac{f_1^2 + f_2^2}{(1 + \chi^2\,b\,f_1)^2 + (\chi^2\,b\,f_2)^2}} \tag{44}$$

$$\tan \phi = -\frac{f_2}{f_1 + b\,\chi^2\,(f_1^2 + f_2^2)} \tag{45}$$

$$L = \frac{\omega^2}{2\,r_0^2\,\gamma\,G} = \frac{-\chi\,f_2}{(1 + b\,\chi^2\,f_1)^2 + (b\,\chi^2\,f_2)^2} \tag{46}$$

Resonance occurs when $\phi = \pi/2$, which corresponds to

$$f_1 + b\,\chi_r^2\,(f_1^2 + f_2^2) = 0 \tag{47}$$

where χ_r^2 corresponds to resonance frequency, ω_r, by

$$\chi_r = \frac{r_0\,\omega_r}{V_s} \tag{48}$$

At resonance

$$\frac{a_r\,G\,r_0}{P} = \frac{f_1^2 + f_2^2}{f_2} \tag{49}$$

and

$$L_r = -\frac{\omega^2}{2\,r_0^2\sqrt{\gamma}\,G}\,\frac{\chi\,r\,(f_1^2 + f_2^2)}{f_2} \tag{50}$$

Because f_1 and f_2 are functions of factor χ, when Poisson's ratio is given, then the value of b can be expressed only in terms of χ_r. Thus, the quantity $\frac{G\,r_0}{P}$ may be expressed in terms of χ_r, where a_r is the displacement amplitude at resonance.

In the compaction of soil by vibration, Quinlan (*6*) believes it reasonable to assume that the degree of densification of a soil is proportional to the elastic vertical displacements of the soil medium. Hence, it is necessary to determine the frequency for which the displacements produced by a transducer are at maximum. This corresponds to

$$\frac{d}{d\chi}\,\frac{a_r\,G\,r_0}{P} = 0 \tag{51}$$

Quinlan, after making a numerical comparison, found that the frequency that causes a phase shift of $\pi/2 = \phi$ also produces maximum displacement. This means that in order to compact a soil by vibration, the frequency of such vibration should be close to resonance frequency. Thus, factors affecting resonance frequency would also affect compaction of soils by vibration.

Reissner, Barkan and others have shown that maximum displacement depends on the Poisson's ratio, the shear modulus, the diameter of the loaded area, the mass of the vibrator, the amplitude of the force, and density of the soil. It is shown that as the Poisson's ratio increases, the damping properties of the soil increase, which results in an increase in dissipation of vibrating energy. Barkan, by using a linear relationship between resonance value of $\frac{a_0\,G\,r_0}{P}$ and $b = \frac{m}{\gamma\,r_0^3}$, found that

$$a_r = \frac{k\,\pi^{1/2}}{G\,A^{1/2}} + \frac{l\,\pi^2\,P_{st}}{G\,\gamma\,A} \tag{52}$$

where k and l are constants of linearity in

$$\frac{a_0\,G\,r_0}{P} = k + lb \tag{53}$$

From this equation γ, the density of the soil, is found to be

$$\gamma = \frac{\pi\,l\,P_{st}}{G\,r_0\left(a_0\,r_0 - \frac{k}{G}\right)} \tag{54}$$

which shows that an increase in the normal static pressure (the weight of the vibrator or the additional surcharge) increases the density of the soil. Similarly, soils with high unit weight would have low resonance amplitude. Under otherwise equal conditions, an increase in the contact area results in a decrease in the resonance amplitude; that is, damping increases. Eq. 52 shows that the resonance amplitude (reduced to unit of exciting force) increases with an increase in the normal static pressure on the soil and decreases with an increase in the contact area.

It is also shown by Barkan that the maximum amplitude of vibration decreases as the depth of the vibrating soil increases. However, both theoretical and experimental results showed that at small depths (approximately in the range 0.2 to 0.5 wavelength) changes in vibration amplitudes are relatively small. This point is of importance in vibratory compaction. The thickness of the compacted layer should, therefore, be selected in such a way that the amplitude of vibration does not drop below an average value at the bottom of the layer.

The power requirement to maintain the vibration is given

by Eq. 46. Eq. 50 gives such a power requirement for resonance frequency. Sung (*7*) gives various curves for the effect on the input power requirements due to mass factor b, frequency, and Poisson's ratio. From these curves it can be seen that the b factor is the most important factor affecting the power requirement. Eq. 40 shows that the b factor depends directly on the mass of the vibrator and indirectly upon the density of the soil and the cube of the radius of the contact area between the vibrator and the soil. Sung's figures show that there is a sharp rise in power requirement as the value of b decreases. This means that an increase in the contact area or an increase in the density of the soil would require an increase in the input power.

As far as vibratory compaction of cohesive soils is concerned, Converse (*8*) believes that "while resonant frequency is an important factor in the vibratory compaction of cohesive soils, it is by no means the only important factor." He attributes the differences in vibratory compaction of cohesive soils and noncohesive soils to the presence of interparticle bonds in the former. Due to the presence of such bonds a force of sufficient magnitude is needed to cause plastic flow of a cohesive soil, which in turn permits the relocation and rearrangement of the particles under vibration. The following are some of his recommendations for accomplishing compaction of cohesive soil by vibration:

1. Operate at or near resonant frequency for the soil oscillator mass.
2. Supply a dynamic force approximately equal to the dead weight of the oscillator.
3. Have the moisture content equal to or slightly higher than the optimum for maximum density as determined in the laboratory.
4. Provide sufficient dead weight to give a unit dead weight bearing pressure on the order of 10 or 12 psi.

Bernhard and Finelli (*3*) from extensive field and laboratory testing of compaction of soil found that (a) a correlation exists between displacement amplitude of vibration and pressure transfer amplitude, where the latter was measured by load cells embedded in the soil; (b) an increase in static dead weight results in a decrease in both resonance frequency and maximum amplitude of vibration, when contact pressure was kept constant; and (c) with constant contact pressure, maximum amplitude of vibration will increase with a decrease in contact radius, but the resonance frequency will decrease.

In order to make theoretical analyses consistent with experimental findings, many modifications are suggested. These modifications generally provide expressions which give results comparable to certain experimental works. For example, the California Institute of Technology (*9*), by modifying Eq. 29, suggested

$$f_r = \frac{\sqrt{g}}{2\pi}\sqrt{840\,\frac{p}{G}\left(1.64 - \frac{F}{W}\right) + 0.55\,\frac{G\,r}{W}} \qquad (55a)$$

where

f_r = resonance frequency, in cps;
p = density of the soil, in pcf;
G = shear modulus of the soil, in psi;
g = gravity, in in./sec/sec;
W = weight of oscillator, in lb;
F = dynamic force, in lb;
r = contact radius of oscillator on soil, in in.; and
$0 < \frac{F}{W} < 1$

As G becomes increasingly large, this Eq. 55a reduces to

$$f_r = \sqrt{\frac{G\,r}{W}} \times \text{a constant} \qquad (55b)$$

which is analogous to Reissner's results for the resonant frequency of a circular base plate on a semi-infinite isotropic medium.

From the results of a large number of field tests it was found that Eq. 55a predicted the measured resonant frequency with an accuracy of ± 1.5 cps for base plates 19.2 and 14 in. in diameter.

CHAPTER FOUR

EXPERIMENTAL INVESTIGATION

This chapter presents the results of the second phase of the investigation, which studied the compaction of soil by the application of dynamic forces on the surface of a confined sample. Due to time and cost limitations, no attempt was made to measure the resonance frequency and/or make comparisons between theory and experiment. Other paving materials, such as asphaltic concrete, portland cement concrete, and different types of granular soils, were also used in this study to a limited degree. For these materials, due to the limitation in useful transducer power and the lack of knowledge of the resonance frequency of these materials, no successful results were obtained. The difficulties encountered and the limited results obtained for such material are briefly presented at the end of this chapter. Some potential uses of sonic energy which were not evaluated in this investigation but whose possibilities are discussed by others are given at the end of this report.

SOIL USED

Sufficient soil for this study was obtained from a construction site on Interstate 71 in downtown Columbus, Ohio.

TABLE 2

RESULTS OF SIEVE ANALYSIS OF A REPRESENTATIVE SOIL SAMPLE

SIEVE SIZE	TOTAL RETAINED (%)	TOTAL PASSING (%)
¾ in.	0.0	100
⅜ in.	0.5	99.5
No. 4	6.2	93.8
No. 8	18.7	81.3
No. 16	39.6	60.4
No. 30	59.1	40.9
No. 50	76.0	24.0
No. 100	88.7	11.3
No. 200	93.5	6.5
Pan	100	0.0

The results of sieve analysis of a representative sample of this soil are given in Table 2 and Figure 5. Table 3 gives the Atterberg limits of the soil.

These tests were all performed according to procedures recommended by the American Society for Testing and Materials (D-422-63 and D-423-61T, D-424-59). Figure 6 shows the moisture-density relations of the soil tested according to ASTM D-698-587 (Method C) and ASTM D-1557-58T (Method C), together with the zero air void curve. The results of such tests are given in Table 4.

VIBRATORY COMPACTION

To compare the moisture-density relation of the soil when compacted by vibration with that of conventional compaction, it was necessary to control the diameter and size of the sample, the size and type of vibrator, the air pressure, the number of layers, and the dwell time (time vibration is applied on each layer). At a first attempt, an air-excited transducer of the rotating-ball type was used. This was fitted with a metal foot attachment (Fig. 7) which can be used to compact the soil in a 4-in. diameter Proctor mold. The weight of the vibrator with its metal foot attached was 5.8 lb.

The soil was compacted in three layers with each layer

TABLE 3

ATTERBERG LIMITS OF REPRESENTATIVE SOIL SAMPLE

DETERMINATION	VALUE
Liquid limit at 25 blows	29.6
Plastic limit	19.4
Plasticity index	10.2

vibrated for 2 min. The test results are given in Table 4. Figure 6 shows the moisture-density curves obtained for various air pressures. The procedure used for vibratory compaction of the soil was as follows:

1. Obtain a 15-lb representative specimen of the soil sample to be tested. If the sample is damp when received from the field, dry it until it becomes friable under a trowel. Drying may be in air or by use of a drying apparatus, such that the sample temperature does not exceed 140 F. Then thoroughly break up all soil lumps and aggregations.
2. Sieve the specimen over a ¾-in. sieve. Break up the coarse material retained on the sieve where possible and sieve again over the ¾-in. sieve.
3. Sieve the material passing the ¾-in. sieve over a No. 4 sieve. Break up the coarse material retained on the sieve where possible and sieve again over the No. 4 sieve.
4. Select approximately 10 lb or more of the representative specimen of soil with sufficient water to dampen it to approximately 6 to 10% below optimum moisture content. Take care that the water is evenly distributed, and that all soil lumps and aggregations are broken up.
5. Weigh the empty mold (with the base but not the collar) to the nearest gram.
6. Form a specimen by compacting the prepared soil in the 4-in. mold (with collar attached) in three equal layers to give a total compacted depth of about 5 in. Compact each layer by inserting the vibrator in the mold in an upright position. Adjust the valve to the pressure for which the test is being run and allow the vibrator to move freely in an up-and-down motion. Hold the vibrator upright and

TABLE 4

RESULTS OF DENSITY-MOISTURE TESTS

STANDARD PROCEDURE				MOD. AASHO PROCEDURE				IMPACT VIBRATOR BD-25[a]			
TEST 1		TEST 2		TEST 1		TEST 2		30-PSI AIR PRESSURE		40-PSI AIR PRESSURE	
WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)
10.6	107.6	12.6	108.9	10.4	127.0	6.1	122.5	13.4	96.7	13.3	95.2
12.5	109.4	14.4	111.1	13.0	123.7	8.0	125.9	15.0	99.3	14.9	99.6
15.9	112.0	16.1	113.2	14.2	120.5	10.5	127.9	16.5	106.7	16.3	108.4
20.4	105.8	20.2	106.5	—	—	11.8	126.8	20.0	104.8	19.5	104.9
—	—	22.9	101.3	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—

[a] Three layers, each vibrated 2 min.

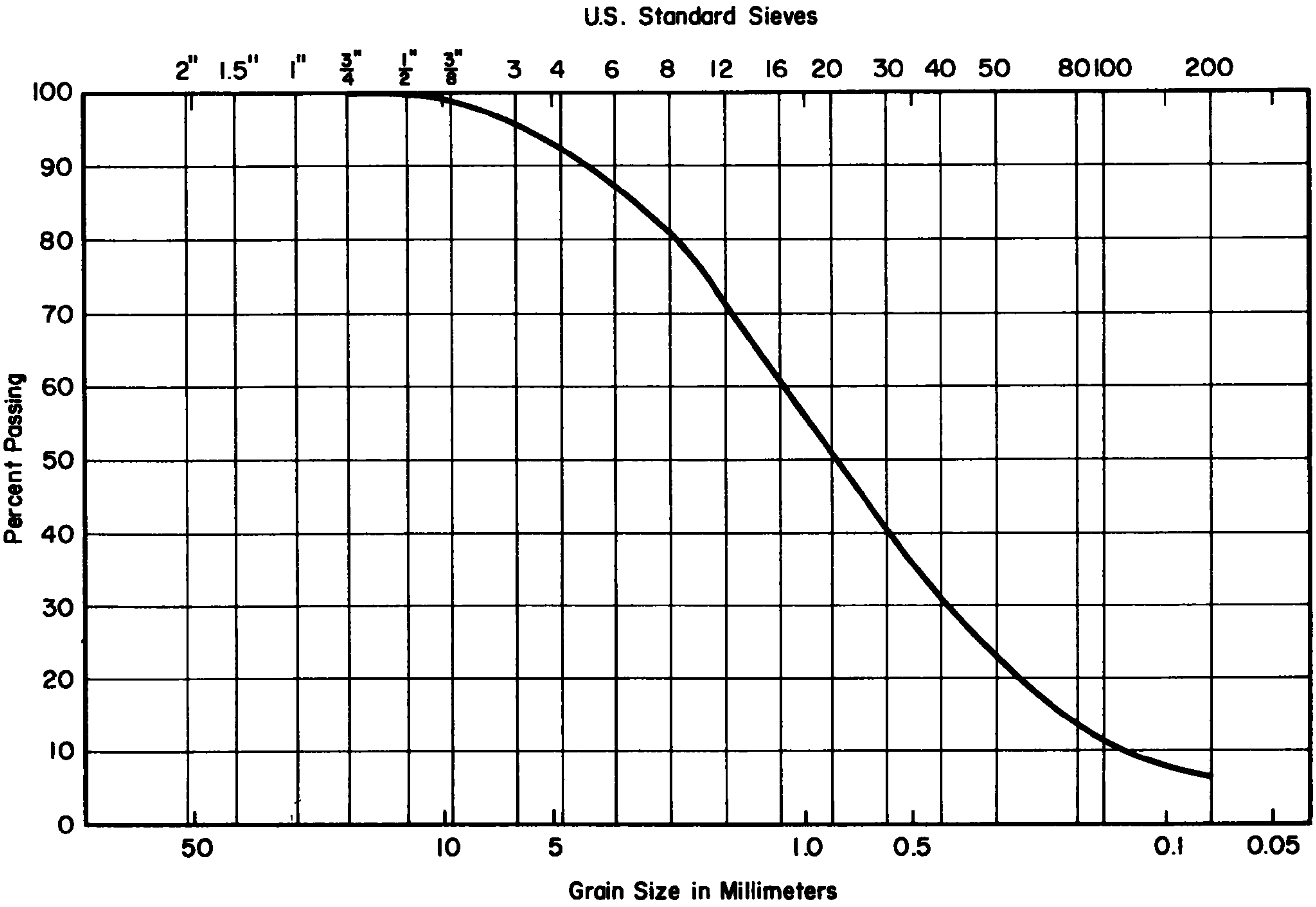

Figure 5. Sieve analysis of a representative soil sample.

adjust its position to prevent binding between the impacting head of the vibrator arm and the sides of the mold. Continue vibration of the soil for the period of time for which the test is being run.

7. Remove the collar and trim off the soil even with the top of the mold, using many small scraping operations with the straightedge, beginning at the central axis and working toward the edge of the mold.

8. After the soil has been made even with the top of the mold and all loose soil has been cleaned from the outside, weigh the cylindrical mold and sample to the nearest gram. Multiply the weight of the compacted specimen and mold, minus the weight of the mold, by 30; record the result as the wet weight per cubic foot of the compacted soil.

9. Obtain a representative sample of the soil in the mold of not less than 400 grams, taking soil from both the top and the bottom of the mold.

10. After determining the weight of the representative sample taken from the mold to the nearest gram, place this sample in an oven maintained at a constant temperature 110 ± 5 C (230 ± 9 F) to dry for at least 12 hr, or until the weight of the sample is observed to be constant, then weigh the sample again to the nearest gram.

11. Meanwhile, remove the remaining soil from the cylindrical mold, breaking up all lumps and aggregations until all will pass a ¾-in. sieve, and 90% will pass a No. 4 sieve as judged by eye. Remix this soil with the remainder of the original sample, and raise the water content by approximately 3%. Take care that the water is evenly distributed and that all soil lumps and aggregations are broken up. Repeat steps 6 through 11 for each increment of water added.

The results shown in Figure 6 were the best obtained

50-PSI AIR PRESSURE		60-PSI AIR PRESSURE		ZERO AIR VOIDS DENSITY	
WATER CONTENT (%)	DRY DENSITY (PCF)	CONTENT WATER (%)	DENSITY DRY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)
13.5	96.1	13.6	97.9	10.0	133.9
15.6	105.3	15.8	108.5	12.0	128.4
18.7	107.0	18.8	108.0	14.0	123.3
20.9	103.1	20.5	104.6	16.0	118.6
—	—	—	—	18.0	114.2
—	—	—	—	20.0	110.2

from 118 tests performed with the BD-25 vibrator. Inconsistency in repeatability of vibrational compaction using the BD-25 vibrator was found to be due to lack of uniform application of the vibratory energy to specimens, as the vibrator was held by hand on top of the specimens and the mold was firmly held to the floor by the operator's feet. To avoid this inconsistency, and also to be able to use high-powered vibrators, a vibration table (Fig. 8) was developed. Use of such a table not only reduced the variation in vibrational energy, but also made it possible to study the effect of surcharge load.

Vibration tests have been run using a surcharge load on different gradations of sand material with good success. With this in mind, it was decided to investigate the effect of testing a cohesive soil under the same conditions. To follow through with this line of testing, the vibration table was used with a rotating-mass transducer clamped to the bottom shaft, which extends vertically downward from the spring-supported table top. Other types of transducers could also be easily attached to this shaft. The variable-speed motor of the transducer made possible testing at different frequency and amplitude levels. The table top is designed to hold a standard 4-in. Proctor mold, but may be modified for use with other mold sizes.

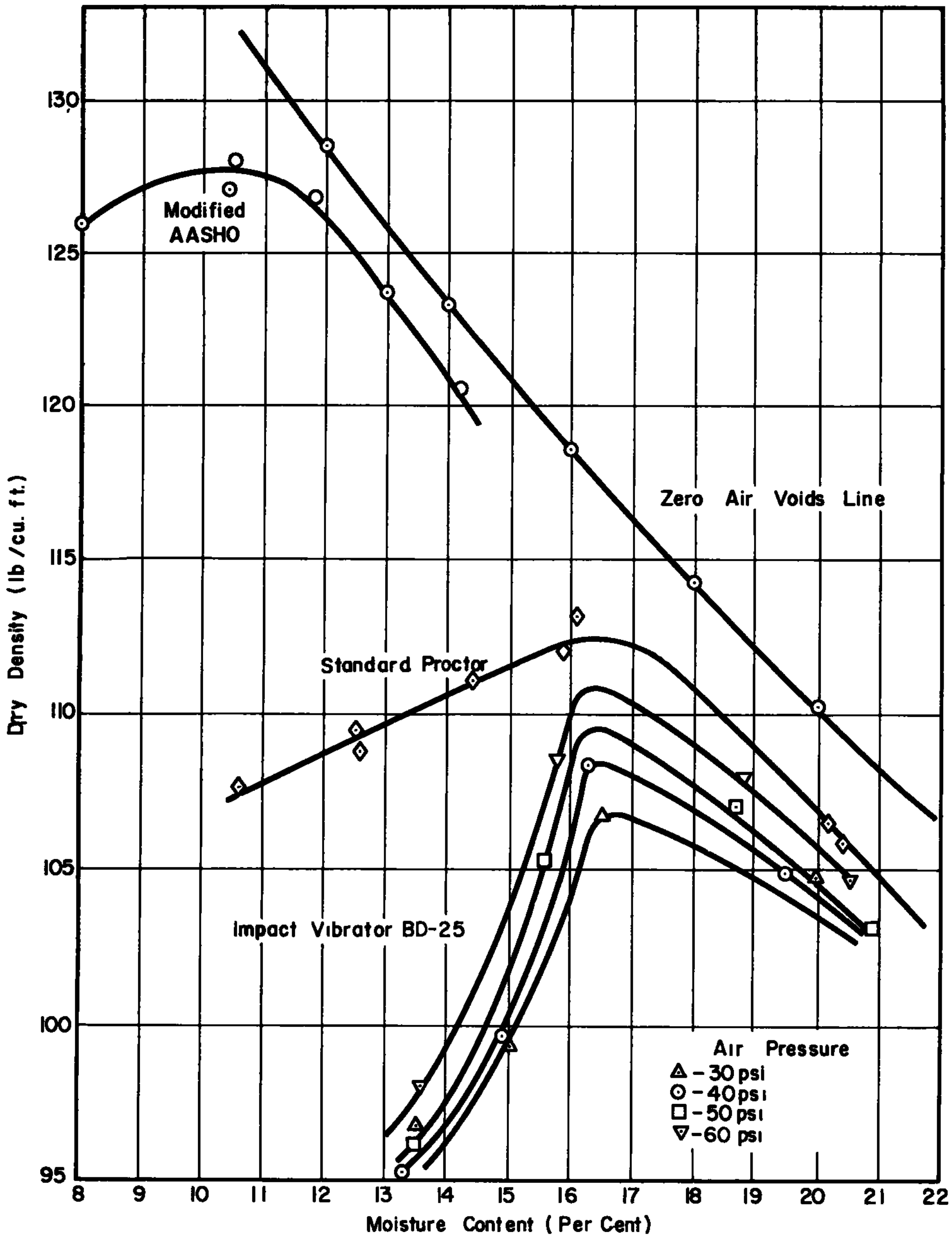

Figure 6. Moisture-density curves for subgrade soil under standard compaction and various vibratory efforts.

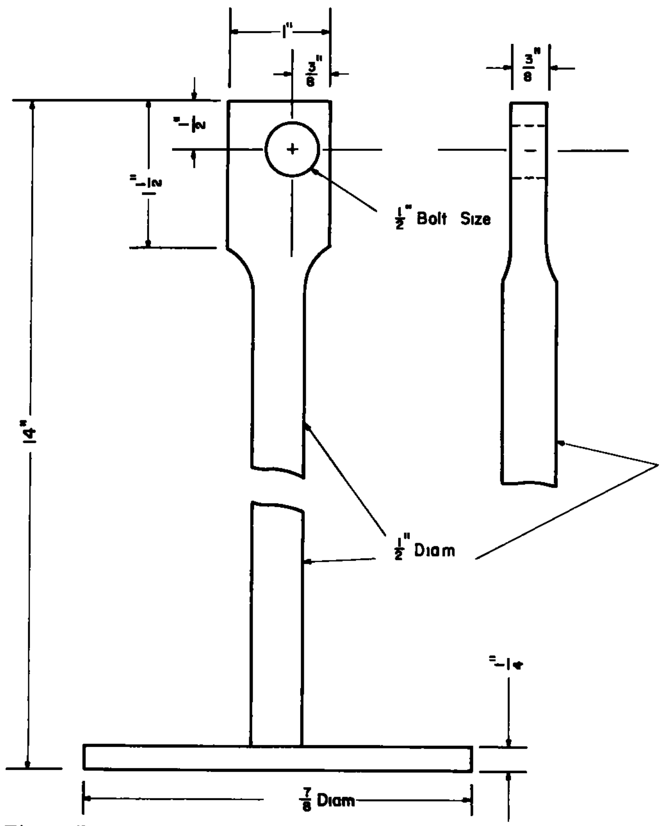

Figure 7. Foot attachment for BD-25 vibrator.

These results show that the BD-25 vibrator does not compact the soil in the same manner as the standard compactors. The standard-type compactor will give a dry density within 3% of maximum for a moisture content which varies from 12.5% to 18.7%. The impact vibratory compactor (at 50-psi air pressure) will give a dry density within 3% of maximum for a moisture content which varies from 15.7% to 19.1%. The moisture content can vary by 6.2% for the standard compactor, but by only 3.4% for the impact vibratory compactor, to obtain a dry density within 3% of maximum. This is indicated by the slopes of the curves on the dry side of the optimum moisture content for the two types of tests (Fig. 6.)

HIGH-FREQUENCY VIBRATORY COMPACTION

During the course of this study a wide-frequency-range power supply of 10-kw capacity was procured by the Ultrasonic Research Laboratory of the Department of Welding Engineering. With its use, it was found that the P-7-B piezoelectric transducers (Fig. 9) are able to deliver much greater mechanical energy. Two of these transducers were sonically tuned for soil compaction. One was used with an attached foot so that there would not be any impact during compaction; the other was used with a loose disc, which rested on top of the soil specimen, thus applying impact

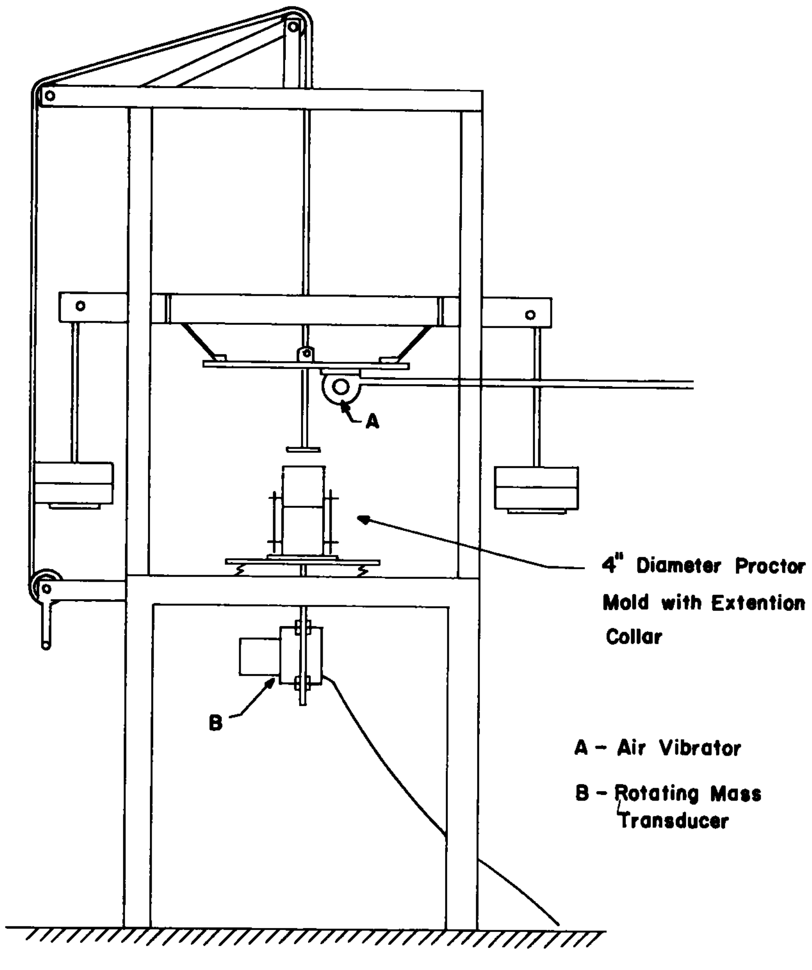

Figure 8. Specially built vibration table.

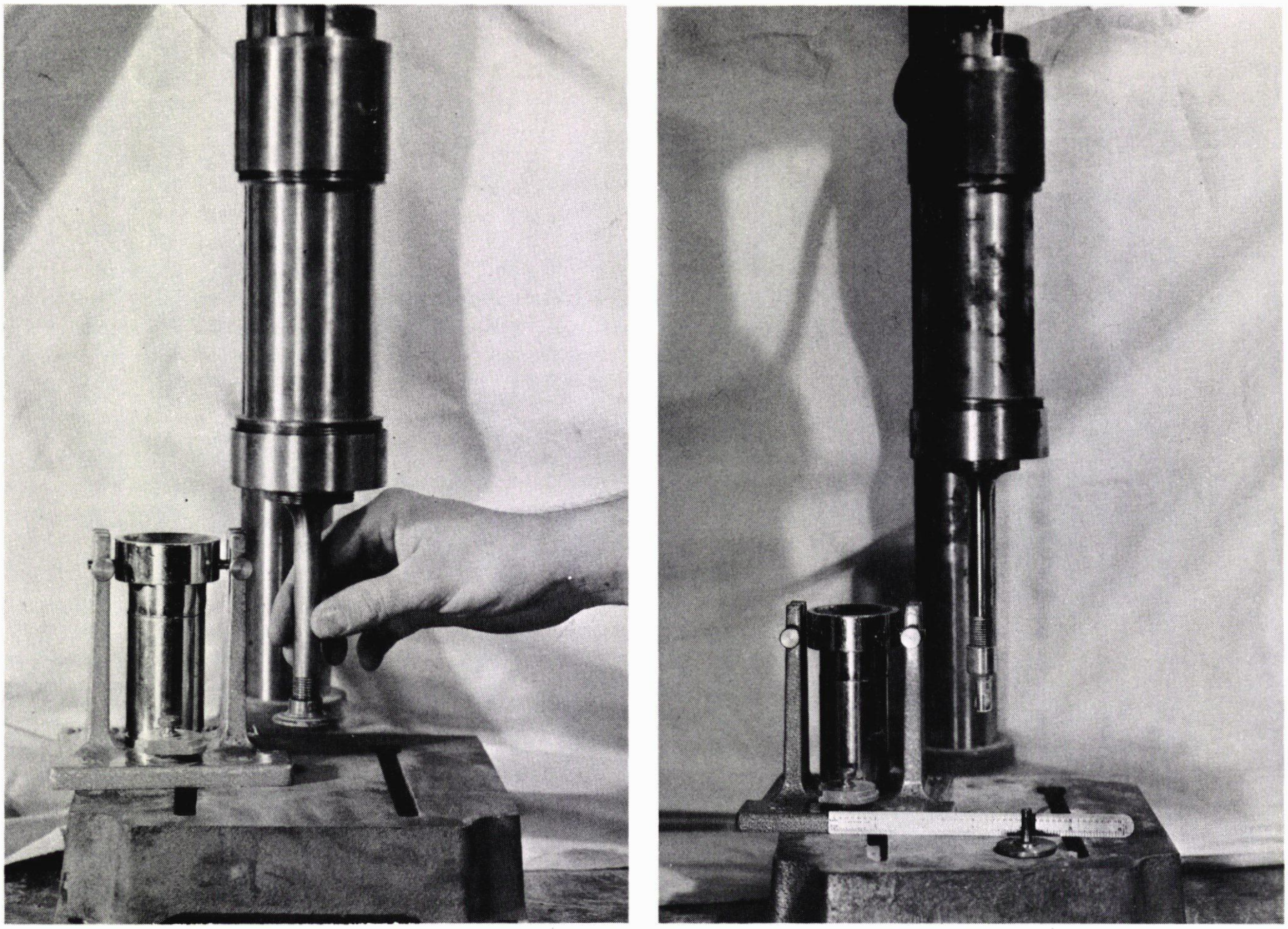

Figure 9. P-7-B piezoelectric transducer with (left) attached foot and (right) impact foot.

vibration to the material. These transducers when perfectly tuned were vibrating at 10.6 kcps. The size of the soil specimens was that of the Harvard miniature mold (1⅜-in. diameter by 2⅞-in., internal dimensions).

Due to the power limitation of these transducers, they could not be used for compaction of soils in a 4-in. diameter Proctor mold. Therefore, to compare the compaction results obtained using high-frequency transducers with those obtained using static compaction and low-frequency vibrators, it was decided to use Harvard miniature size specimens for this comparison. Consequently, three methods of compaction were employed, as follows:

1. Conventional Harvard miniature method (*10*).
2. A rotating-ball air transducer Model BD-16.
3. Two piezoelectric transducers Model P-7-B, one with attached foot and one with a loose foot.

The variables used in this part included (a) moisture content of the soil, (b) number of layers used for compaction, (c) duration of vibration, (d) contact pressure, and (e) additional surcharge weights for P-7-B transducers. The tests performed included determination of (a) dry density, (b) creep modulus, (c) stress-strain curves, and (d) unconfined compressive strength of the compacted specimens.

In what follows, typical results are presented. Due to the bulk of the data, attempts are made to present (a) typical results of series of similar tests, and (b) those results which show some significant changes.

Moisture-Density Relationship

The moisture-density relationship for this subgrade soil when compacted in a Harvard miniature mold with a 17-lb tamper is shown in Figure 10. This result was obtained according to the procedure described by Wilson (*10*). The tamper used was the smallest available. The optimum moisture content and maximum dry density obtained are comparable to the results obtained with the standard Proctor procedure (Fig. 6). The soil was compacted in four layers with 20 blows applied to each layer.

Table 5 gives moisture content, density, and unconfined compressive strength for a typical series of tests on specimens made in a Harvard miniature mold by a BD-16 rotating-ball transducer. These specimens were placed in five layers, each subjected to vibration for 1 min at 30-psi air pressure (8,500 vibrations per minute). The moisture-density results are shown in Figure 11. The optimum moisture content and the maximum dry density lie between the values obtained for the same soil when compacted accord-

ing to AASHO and modified AASHO procedure (Fig. 6). The unconfined compressive strength (Fig. 12) was performed according to ASTM Standard D-2166-63T. Figure 13 shows a typical stress-strain curve for the specimen compacted at moisture content close to optimum.

Table 6 contains typical moisture-density test results for the specimens compacted by a P-7-B transducer under four different conditions, as follows:

1. Attached foot, no additional weight.
2. Attached foot, 2.5 lb additional weight.
3. Unattached foot, no additional weight.
4. Unattached foot, 2.5 lb additional weight.

All specimens of the P-7-B series were compacted in four layers with vibrations maintained for 30 sec on each layer. The following procedure was followed for the preparation of the soil sample and for its compaction:

1. Thoroughly break up all lumps and aggregations. Sieve the soil over a No. 12 sieve and discard any coarse material.

2. To obtain one point on the moisture-density curve, select 160 grams of soil passing the No. 12 sieve and add sufficient water to raise the moisture content to approximately the value desired. Mix the sample thoroughly, breaking up all lumps and aggregations until all of the sample will pass a No. 8 sieve. If the sample is too wet to be passed through a No. 8 sieve, sieve over a No. 4 sieve whenever possible.

3. Place the prepared sample in a small glass jar with a tight fitting cover and store for at least 12 hr.

4. After the sample has been stored for at least 12 hr, put approximately two heaping teaspoonfuls of soil into the Harvard compaction apparatus with base plate and

TABLE 5

MOISTURE CONTENT, DENSITY, AND UNCONFINED COMPRESSIVE STRENGTH OF SPECIMENS COMPACTED BY BD-16 VIBRATOR [a]

WATER CONTENT (%)	DRY DENSITY (PCF)	UNCONF. COMPR. STR. (PSI)
11.1	104.9	53.0
13.0	113.2	68.7
13.7	116.9	67.6
14.5	119.7	73.9
16.2	116.2	78.9
16.9	114.0	39.1
17.0	114.1	46.0
18.6	110.5	25.9
23.0	99.9	2.7

[a] Five layers, 1 min each, 30-psi air pressure.

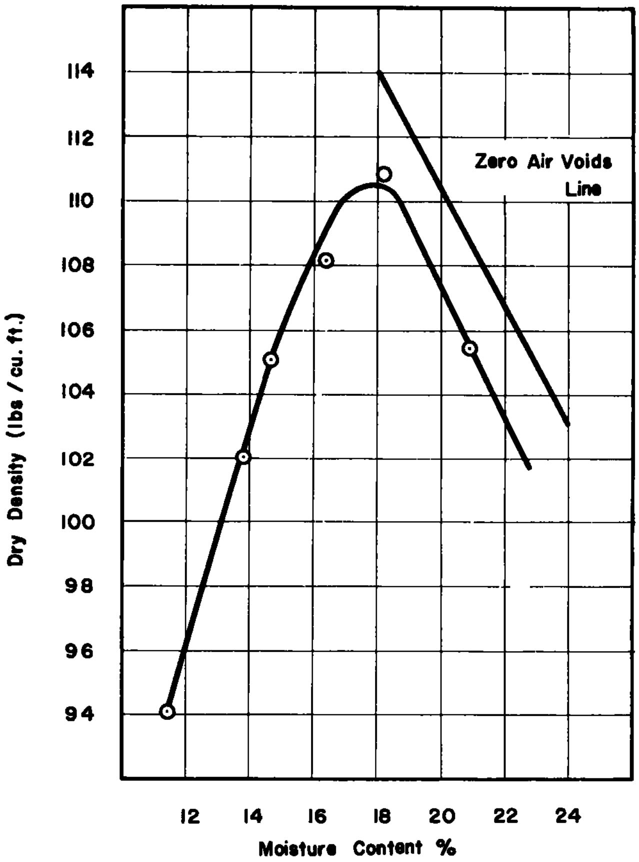

Figure 10. Moisture-density curve for Harvard miniature compacted specimens; four layers, 20 tamps each, with 17-lb tamp.

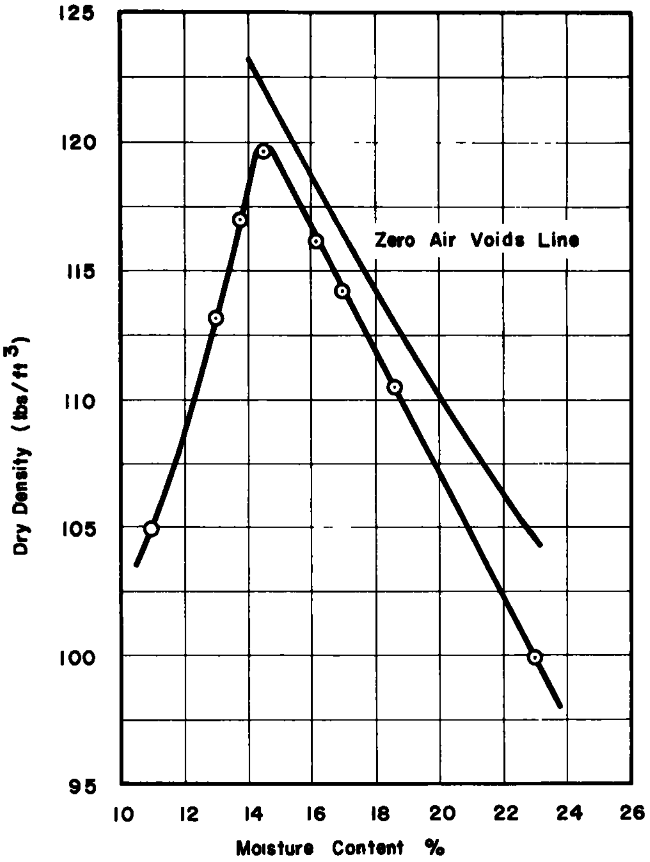

Figure 11. Moisture-density curve for BD-16 compacted specimen; five layers, 1 min each, 30 psi.

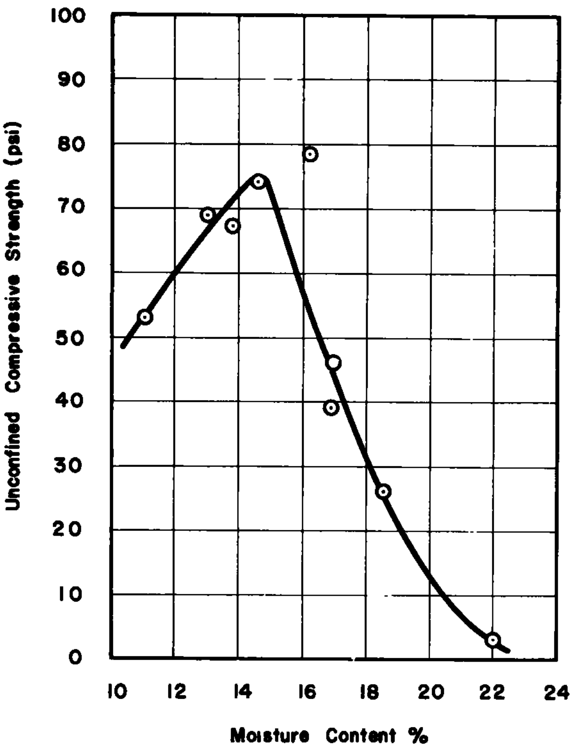

Figure 12. Effect of moisture on unconfined compressive strength for BD-16 compacted specimen; five layers, 1 min each, 30 psi.

mold collar attached. Lower the P-7-8 transducer into the mold and allow it to vibrate in contact with the soil for the period of time desired.

5. Repeating Step Four, successively compact three more layers in the mold, allowing the transducer to remain in contact with the soil for the same period of time for each of the four layers compacted. The final layer should extend at least ⅜ in. into the mold collar.

6. Use the excess soil remaining in the glass jar for the determination of water content.

7. Weigh the mold containing the compacted soil to the nearest 0.1 gram. Subtract the weight of the mold, the resulting net weight being numerically equal to the net unit weight of compacted soil in pounds per cubic foot.

8. Remove the specimen from the mold with the sample ejector, and place in a suitable container to hold it until an unconfined compression test can be run.

9. When possible, compact additional specimens until points have been established on both sides of optimum moisture content.

Figure 14 shows some typical moisture-density curves for the soil when compacted with a P-7-B transducer with attached foot. The upper curve shows the result when the static compactive force was equal to the weight of transducer plus an additional 2.5-lb surcharge; the lower curve shows the similar result for a static force equal to the weight of the transducer only. Figure 15 shows similar

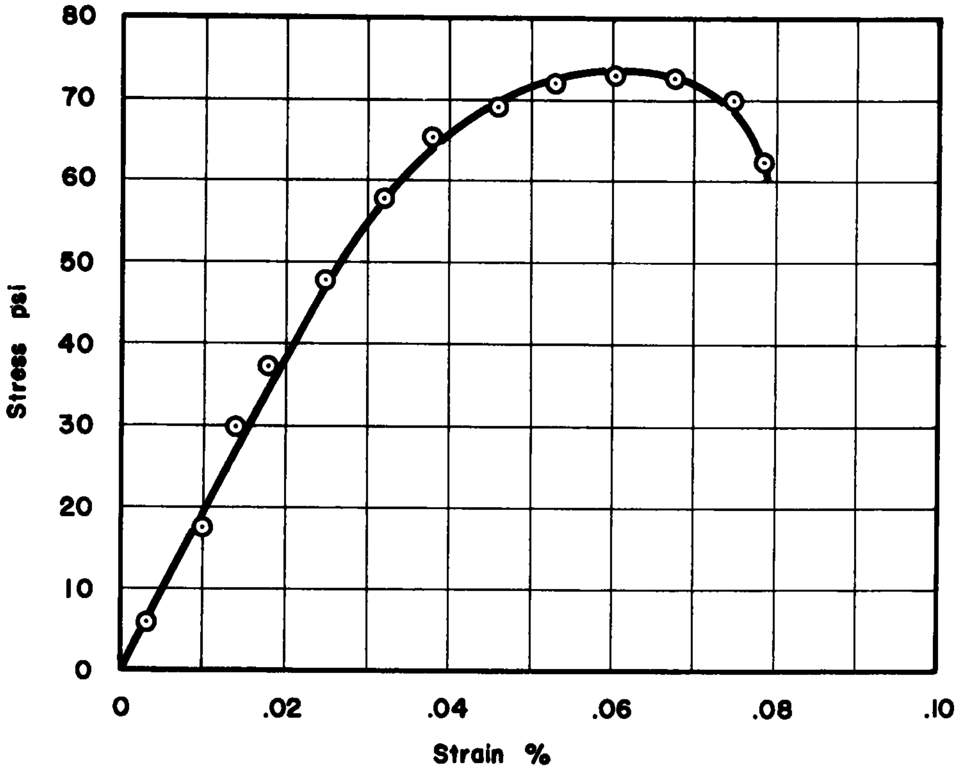

Figure 13. Stress-strain curve for BD-16 compacted specimen; five layers, 1 min each, 30 psi, moisture 14.5%, dry density 119.7 pcf.

TABLE 6

RESULTS OF MOISTURE-DENSITY TESTS FOR SPECIMENS COMPACTED BY P-7-B TRANSDUCER [a]

ATTACHED FOOT				UNATTACHED FOOT			
NO ADDED WEIGHT		2.5-LB ADDED WEIGHT		NO ADDED WEIGHT		2.5-LB ADDED WEIGHT	
WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)	WATER CONTENT (%)	DRY DENSITY (PCF)
11.7	83.0	12.1	84.5	11.6	85.3	12.1	86.3
11.7	83.8	13.0	86.3	12.9	88.6	12.9	87.1
12.9	89.3	14.0	88.0	13.9	90.7	14.0	88.5
13.0	85.9	13.8	88.8	16.0	96.5	15.8	97.7
14.0	88.2	15.8	97.3	17.4	99.2	17.4	103.5
13.8	88.8	16.2	103.1	16.3	94.0	16.2	103.1
13.6	88.2	18.2	105.4	18.2	99.4	18.2	105.4
13.5	90.1	—	—	—	—	—	—
15.7	95.2	—	—	—	—	—	—
17.6	90.6	—	—	—	—	—	—
21.0	97.1	—	—	—	—	—	—
15.7	94.0	—	—	—	—	—	—

[a] Four layers, 30 sec each.

curves for a P-7-B transducer with unattached foot. With both the attached foot and the unattached foot it was extremely difficult to obtain a reproducible result for moisture contents above 17 or 18%. At these moisture contents, due to the wetness of the soil, a large amount of soil was sticking to the transducer. This extra weight on the transducer caused a change in the weight for which it was tuned. The out-of-tune transducer could not operate at the maximum power, consequently no compaction could be achieved. Therefore, it was not possible to establish an optimum moisture content for this type of compaction. However, these results show clearly how effective an additional static weight is on the degree of densification. An increase in static force in both cases caused an increase of 7 to 10% in density. This increase in density, however, is only near the optimum moisture content; in other words, at high moisture contents. At low moisture content, however, additional static forces did not have any effect on density.

Figure 16 shows another typical moisture-density relationship obtained by using a P-7-B vibrator with unattached foot. The soil in this case was compacted in five layers, at 30 sec each, and over a wide range of moisture content. The upper curve is for the case where an additional weight of 1.86 lb was used as surcharge; the lower curve gives similar results for the case where no surcharge was used. These results, also given in Table 7 together with the unconfined compressive strength, show that (a) an increase in the number of layers results in an increase in the density at all moisture contents; (b) the effectiveness of the surcharge is more pronounced than in Figure 15; (c) at low moisture contents the density first decreases with an increase in moisture content and then starts to increase with an increase in moisture content.

This point was also observed by Barkan (*5*) when studying the effect of vibrations on the porosity of soils. He stated that the coefficient of vibratory compaction (a measure of densification) decreases sharply at low mois-

TABLE 7

RESULTS OF MOISTURE-DENSITY AND UNCONFINED COMPRESSIVE STRENGTH TESTS FOR SPECIMENS COMPACTED BY P-7-B TRANSDUCERS WITH UNATTACHED FOOT [a]

NO ADDED WEIGHT			1.86-LB ADDED WEIGHT		
WATER CONTENT (%)	DRY DENSITY (PCF)	UNCONF. COMPR. STR. (PSI)	WATER CONTENT (%)	DRY DENSITY (PCF)	UNCONF. COMPR. STR. (PSI)
10.0	92.6	—	10.0	98.0	32.0
12.3	89.1	19.2	12.5	76.2	28.3
14.7	95.5	17.7	15.0	107.5	47.7
16.4	103.0	25.4	16.1	112.3	47.0
16.4	101.8	21.0	16.3	112.8	45.0

[a] Five layers, 30 sec each.

ture content, but as moisture content increases this coefficient gradually grows. He found that when moisture content reaches a certain value (in his case 17%) the coefficient of vibratory compaction approaches its maximum. Any further increase in moisture content will cause a decrease in this coefficient. The initial drop in density with increase in moisture content may also be explained by Converse's (9) opinion that in vibratory compaction of cohesive soil "it is necessary to break the bond holding the particles together before it is possible for them to shift into a more dense configuration." At very low moisture content, the soil is placed in the mold in pulverized condition and vibratory energy would cause shifting of these small particles into a more dense position. As moisture is increased slightly, however, the particles attach to each other and create soil lumps, which require more energy for displacement unless the bonds are broken. Further addition of moisture will (a) weaken the bond and (b) act as lubricant which facilitates the movement of the particles and thus results in higher densities.

Creep Test

A series of uniaxial creep tests was performed on specimens compacted by a P-7-B transducer and a rotating-ball air vibrator to study the effect of different vibratory compaction on strength characteristics of soil. Table 8 gives the moisture content and density, the method of compaction, the degree of compaction, and the corresponding stress levels to which several specimens were subjected during the creep tests. The preparation of these specimens was the same as explained in the previous section.

Two levels of force amplitude were used for compaction with the P-7-B transducer: (a) no additional weight, and (b) 1.86-lb additional weight. Specimens compacted by

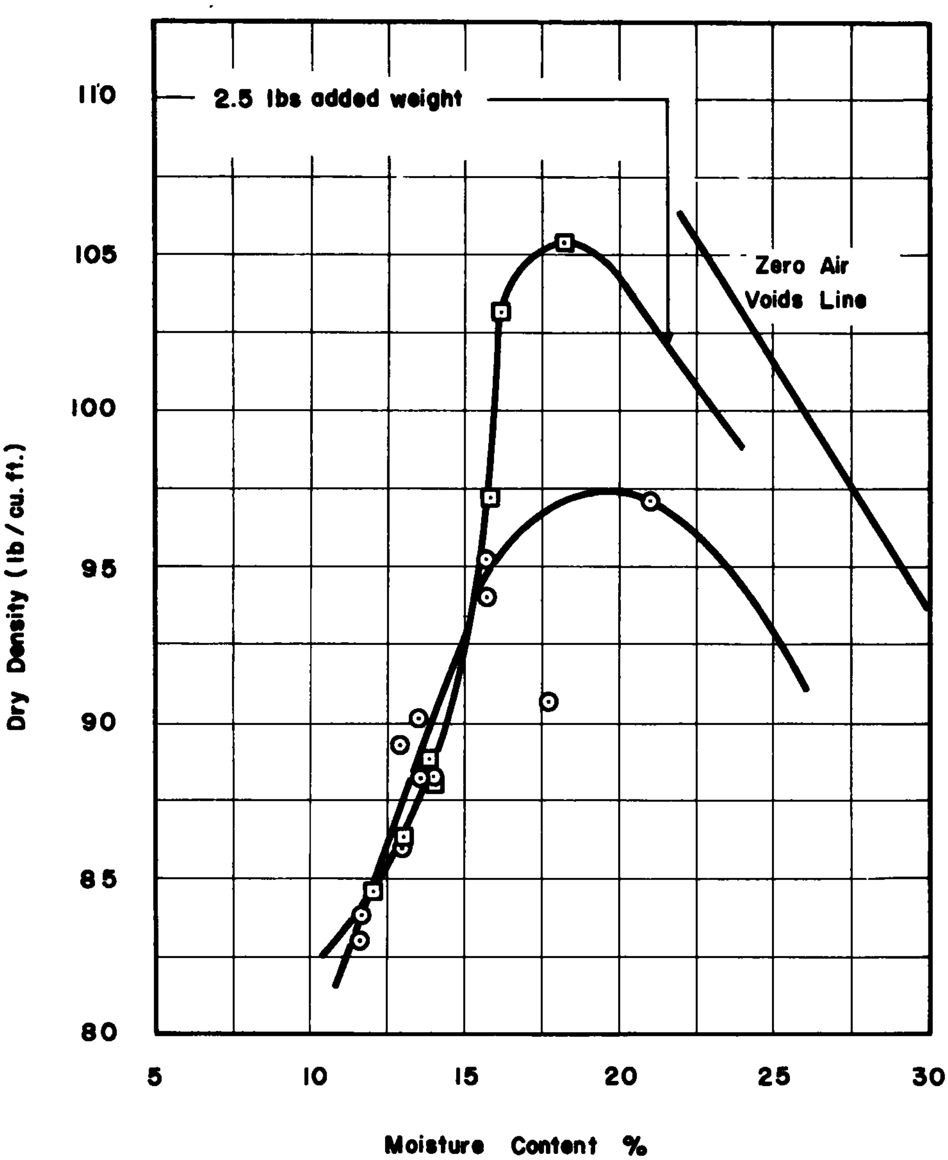

Figure 14. Moisture-density curve for specimen compacted by P-7-B with attached foot.

TABLE 8

MOISTURE–DENSITY–STRESS LEVELS OF SPECIMENS TESTED IN CREEP

TRANSDUCER	SAMPLE NO.	MOISTURE CONTENT (%)	DRY DENSITY (PCF)	CREEP STRESS (PSI)
P-7-B,[a] 1.86-lb added load	R-6	10.0	98.0	7.39
	R-17	12.5	96.2	7.39
	R-7	15.0	107.5	7.39
	R-22	16.3	112.8	3.69
	R-28	16.1	112.3	7.39
P-7-B,[a] no added load	R-4	10.0	92.6	7.39
	R-12	12.3	89.1	7.39
	R-15	14.7	95.5	7.39
	R-16	16.4	103.0	11.09
	R-24	16.4	101.8	7.39
BD-16, 30 psi	R-37	10.5	100.2	14.78
	R-41	11.6	99.3	14.78
	R-32	13.4	109.9	14.78
	R-45	14.3	109.9	14.78
	R-9	15.0	114.3	14.78
	R-49	15.7	117.7	14.78
	R-53	18.6	107.0	3.69
	R-57	20.9	103.6	1.84
BD-16, 40 psi	R-38	10.4	101.1	14.78
	R-42	11.6	104.0	14.78
	R-46	14.3	114.4	14.78
	R-50	15.7	112.6	14.78
	R-54	19.0	106.1	3.69
	R-58	20.6	103.7	1.84

[a] With unattached foot.

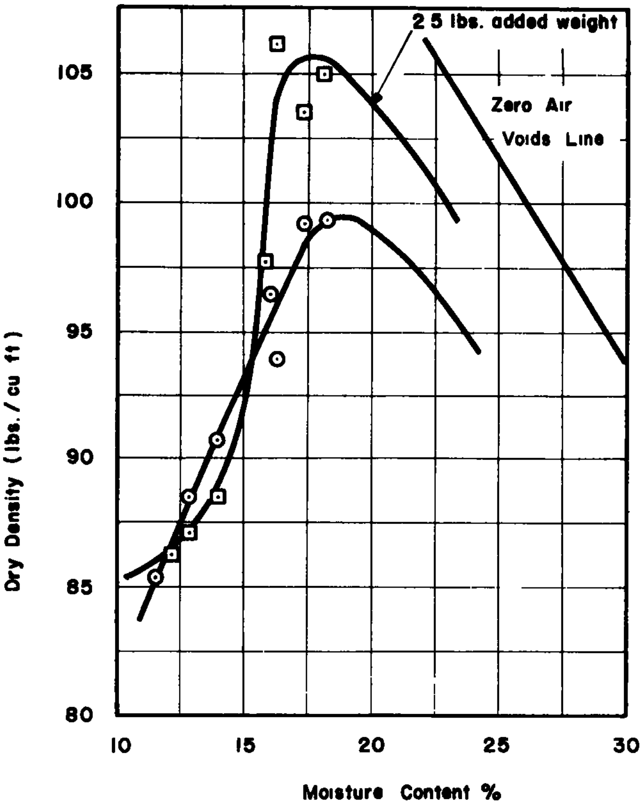

Figure 15. Moisture-density curve for specimen compacted by P-7-B with unattached foot.

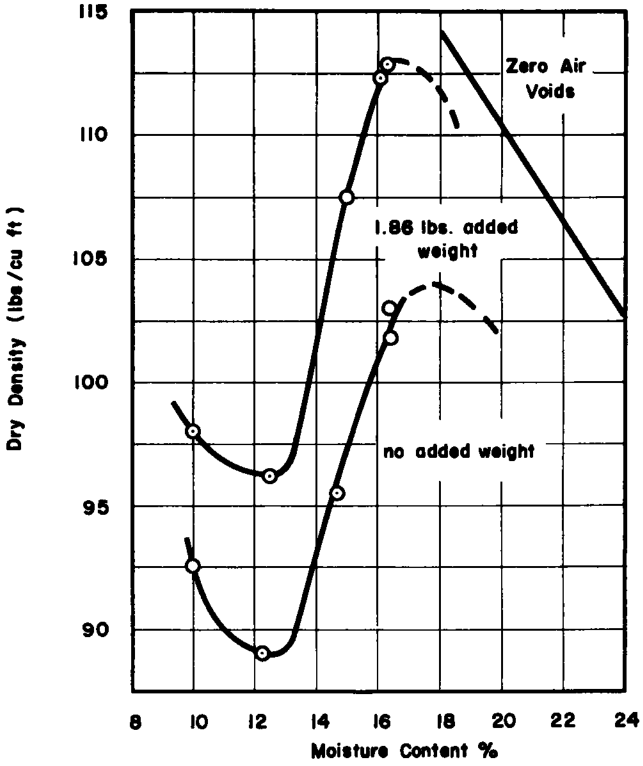

Figure 16. Moisture-density curve for specimen compacted by P-7-B with unattached foot; five layers, 30 sec each.

air vibrator were also subject to two levels of compactive effort: (a) 30-psi air pressure, and (b) 40-psi air pressure. All specimens were compacted in five layers; those compacted with the P-7-B transducer were subjected to 30-sec vibration, the rest being subject to 1-min vibration. The creep test apparatus (Fig. 17) consisted of a triaxial cell with the creep load applied to the specimen through a loading frame. Deformation was recorded by means of an LVDT transducer connected to a Varian recorder having chart speeds of 1 ft per minute and 1 in. per minute. Either of the speeds was used, depending on the speed of specimen deformation and the sensitivity required.

The amount of deformation was limited to values smaller than 20×10^{-3} in., which corresponded to strains smaller than 1%. This limitation was necessary in order to have linear response, and thus be able to use creep moduli of the samples for comparison. After the set deformation was attained, the load was taken off. The recorder was allowed to run until the deformation became constant. Different loads had to be used on some specimens in order to maintain the deformation within the specified limit of 1%. Figures 18 through 21 show the strain-time relationship obtained for the compacted specimens in creep test. The curve designations refer to Table 8, which gives the moisture content and density of each specimen and the stress level to which it was subjected. For example, in Figure 18, curve R-9 is for the specimen which had a moisture content of 15%, a dry density of 114.3 pcf, and was tested under 14.78-psi creep stress. Figures 18-21 show the deformations of the specimens under the first 240 sec of load and the first 60 sec of unloading. From these figures it can be seen that regardless of moisture content, density, type of compaction, and level of stress, all the specimens showed an instantaneous deformation at the start and a gradual decrease in rate

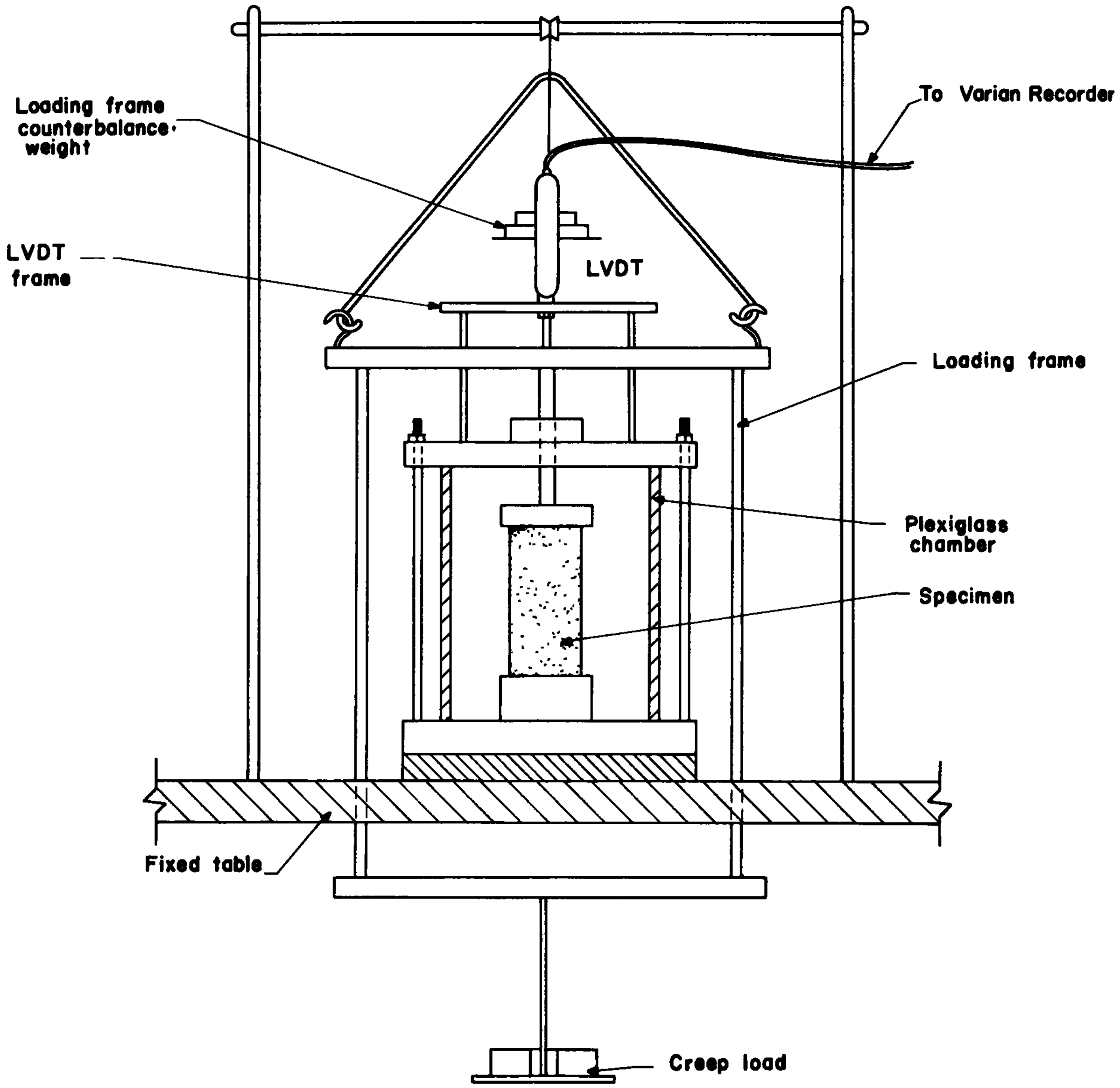

Figure 17. Creep testing apparatus.

of deformation as time increases. Similarly, upon unloading all the specimens showed an instantaneous recovery, a delayed recovery, and a permanent deformation.

To be able to study the effect of moisture content, density, and type and degree of compaction, it was necessary to eliminate the effect of the stress level on the strain of the

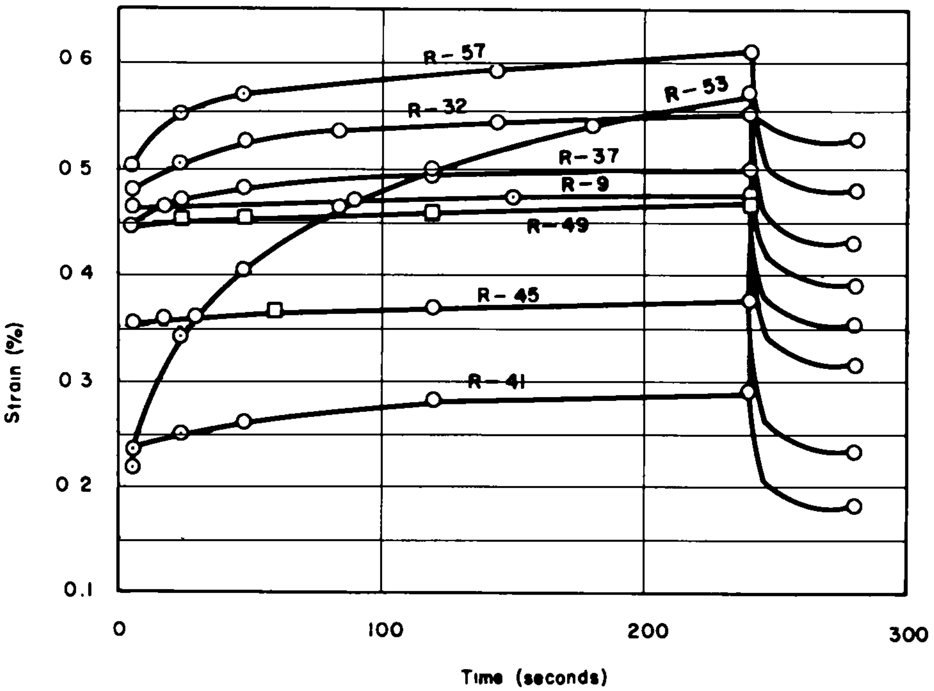

Figure 18. Strain-time curves for specimens compacted by BD-16; five layers, 30 sec each, 30 psi.

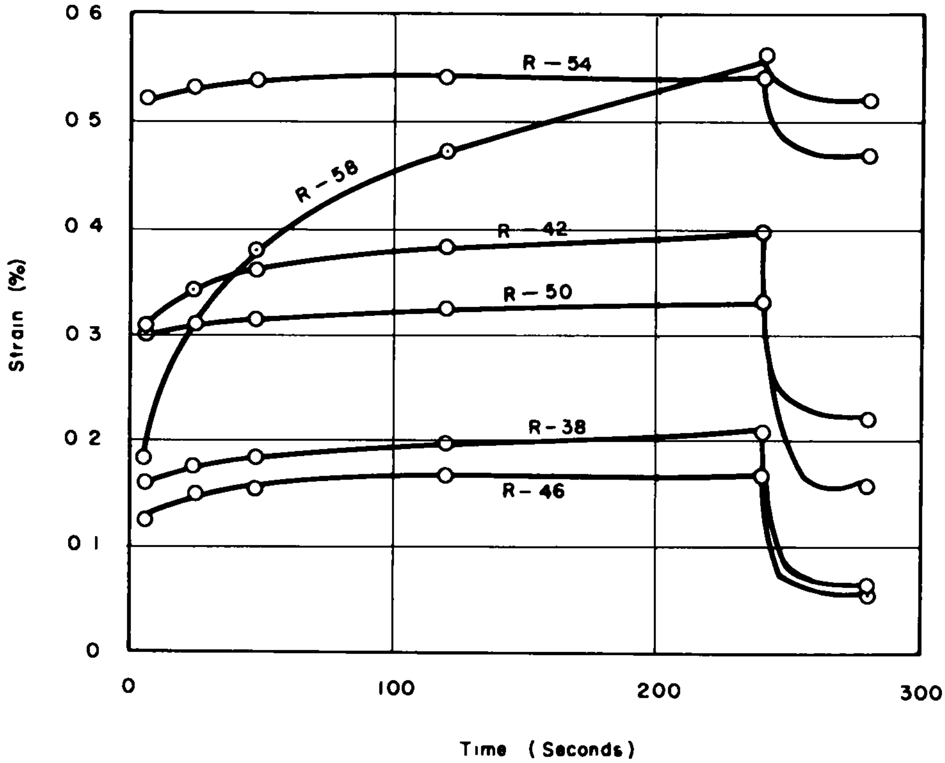

Figure 19. Strain-time curves for specimens compacted by BD-16; five layers, 30 sec each, 40 psi.

specimens. This was achieved by calculating the creep modulus, E_c (t), of each specimen and plotting it versus time. The creep modulus at any instant is defined as the ratio

$$E_c\ (t_i) = \frac{\sigma}{e\ (t_i)} \qquad (56)$$

where

σ = stress, in psi; and
$e\ (t_i)$ = strain at time t_i.

Figures 22 through 25 show the relationship of creep modulus to time for the same conditions as Figures 18 through 21. If the soil were a completely elastic material,

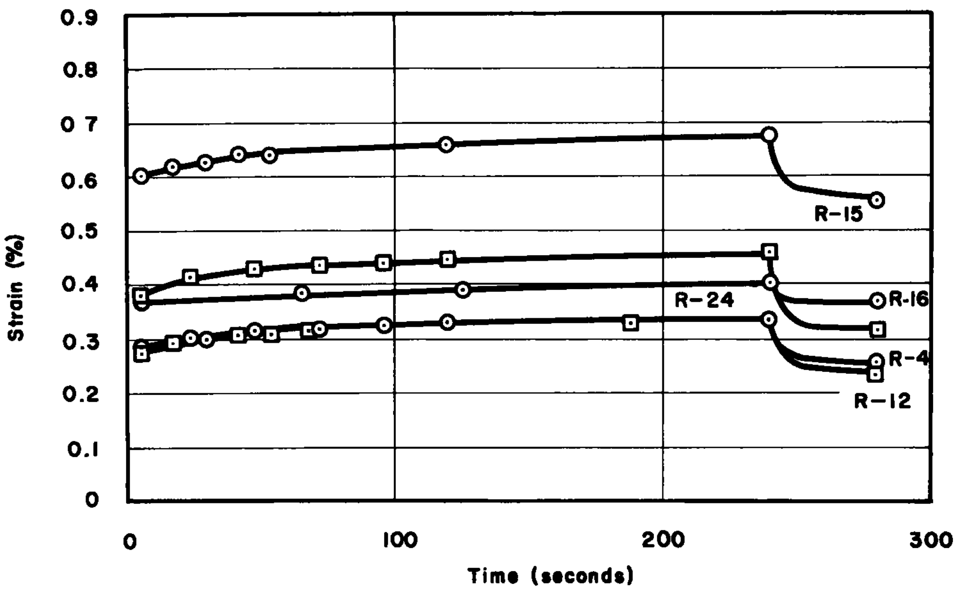

Figure 20. Strain-time curves for specimens compacted by P-7-B with unattached foot; five layers, 30 sec. each.

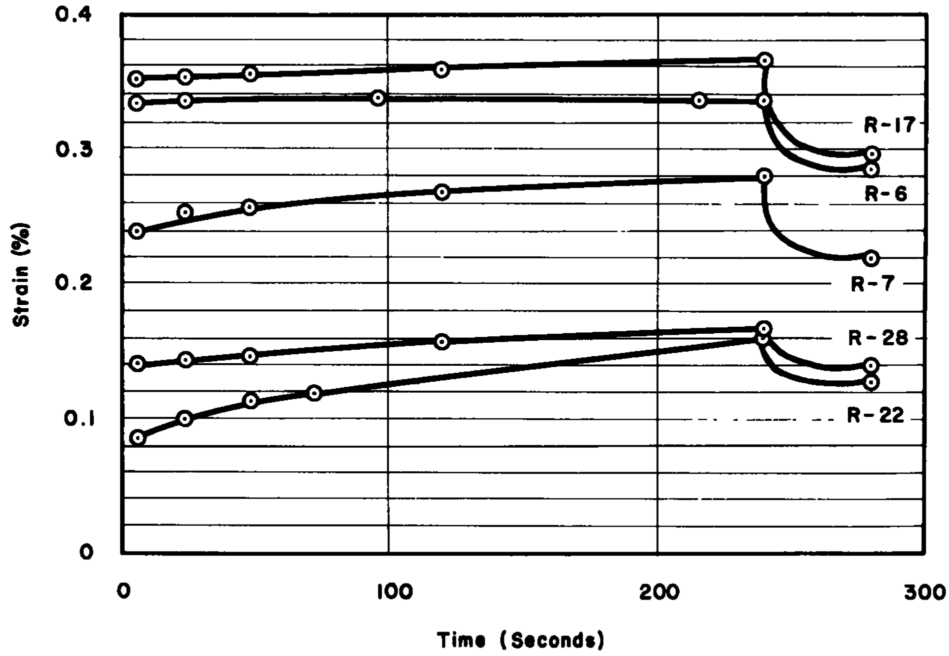

Figure 21. Strain-time curves for specimens compacted by P-7-B with unattached foot; added load 1.86 lb, five layers, 30 sec each.

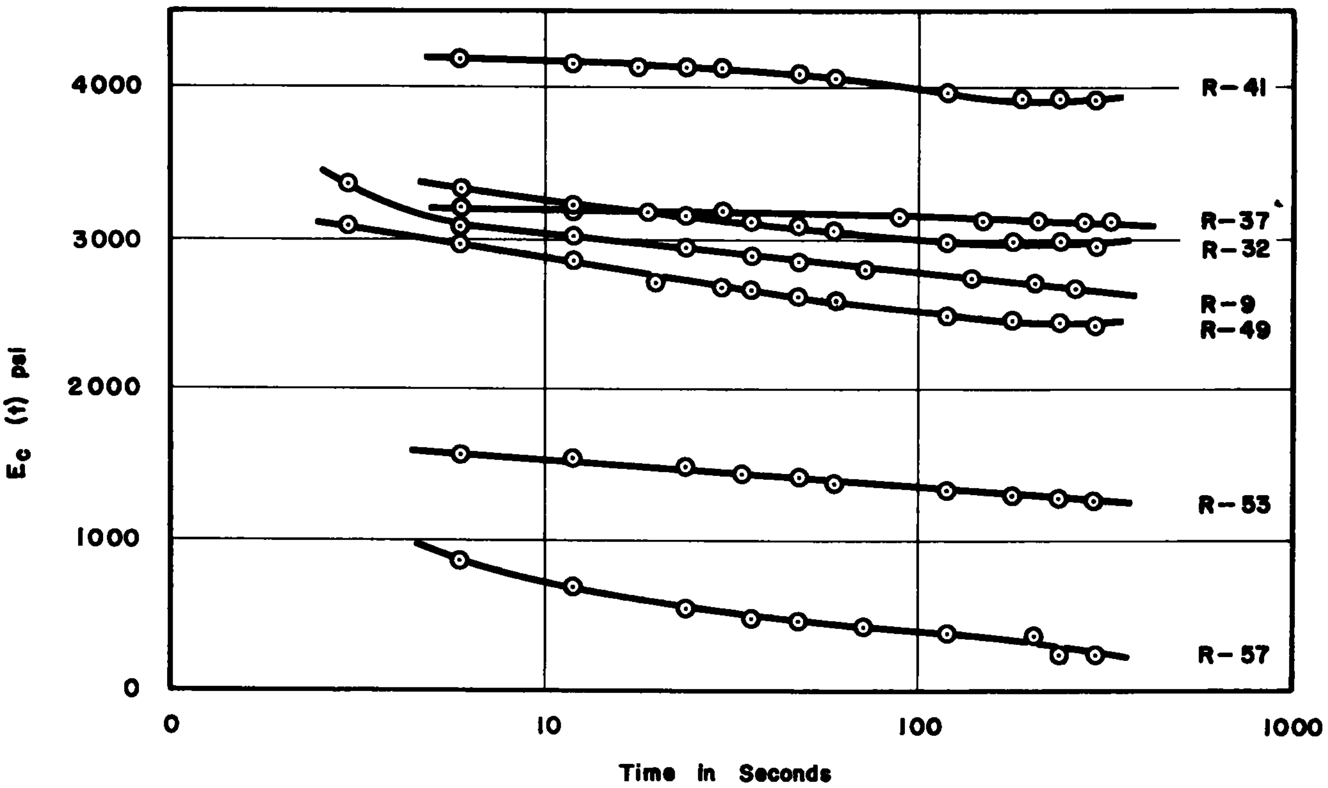

Figure 22. Creep modulus vs time for specimens compacted by BD-16; five layers, 30 sec each, 30 psi.

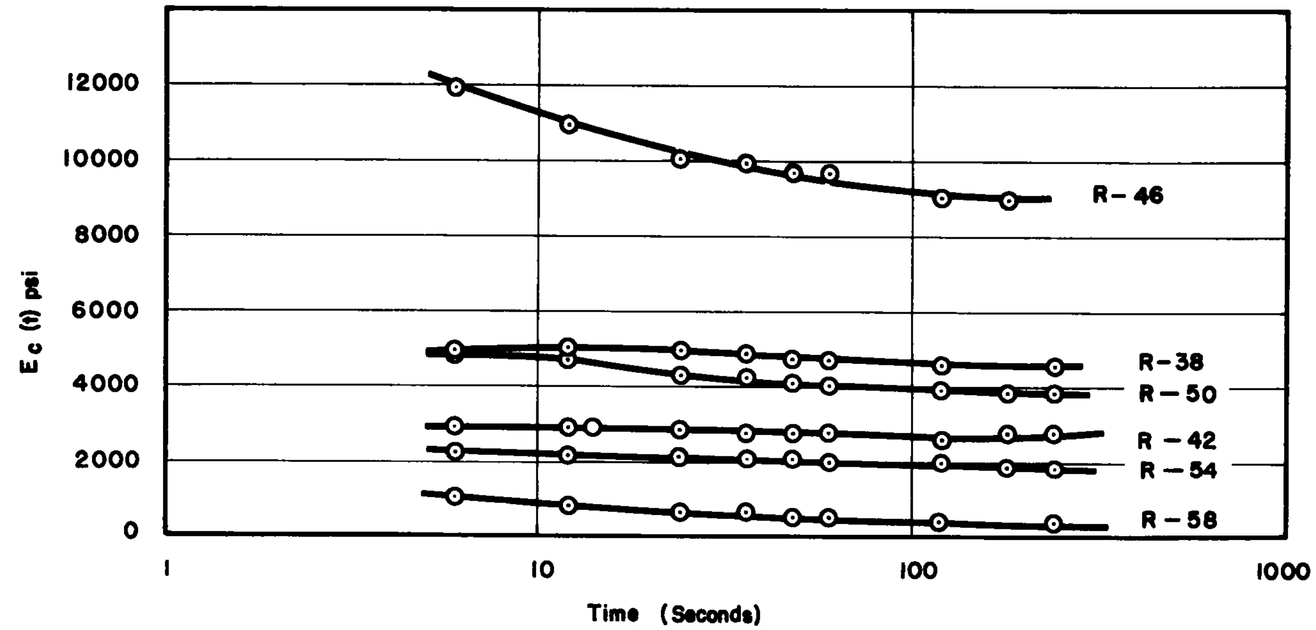

Figure 23. Creep modulus vs time for specimens compacted by BD-16; five layers, 30 sec. each, 40 psi.

the creep modulus would have been the same as the modulus of elasticity and would not be time dependent. However, variation of such a modulus shows that the soil specimens tested deviated from elasticity. This indicates that elastic analyses when used for soils should be modified to account for this deviation.

These results, although limited, indicate that, in general, the creep modulus is related to moisture content and density of the soil, and the method of compaction does not affect the results significantly. In other words, when two specimens are compacted by two different methods and have the same density and moisture content they would also have

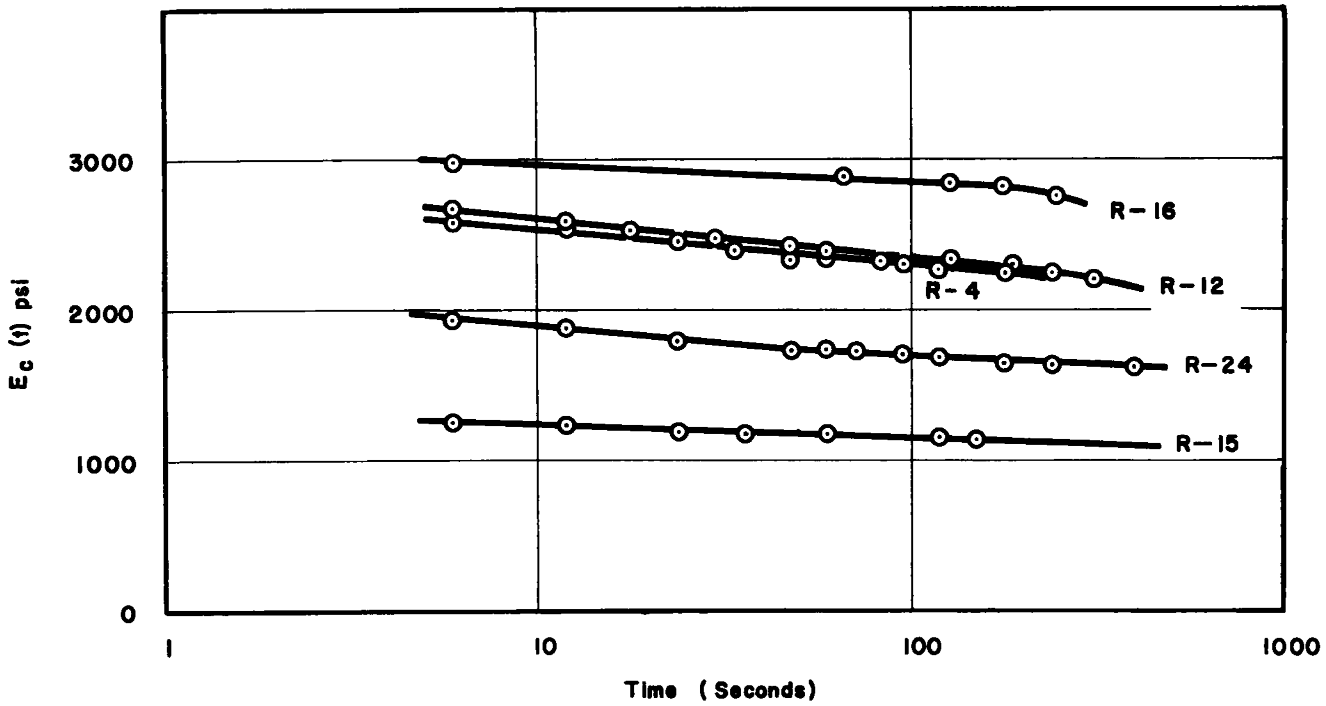

Figure 24. Creep modulus vs time for specimens compacted by P-7-B with unattached foot; five layers, 30 sec each, no added load.

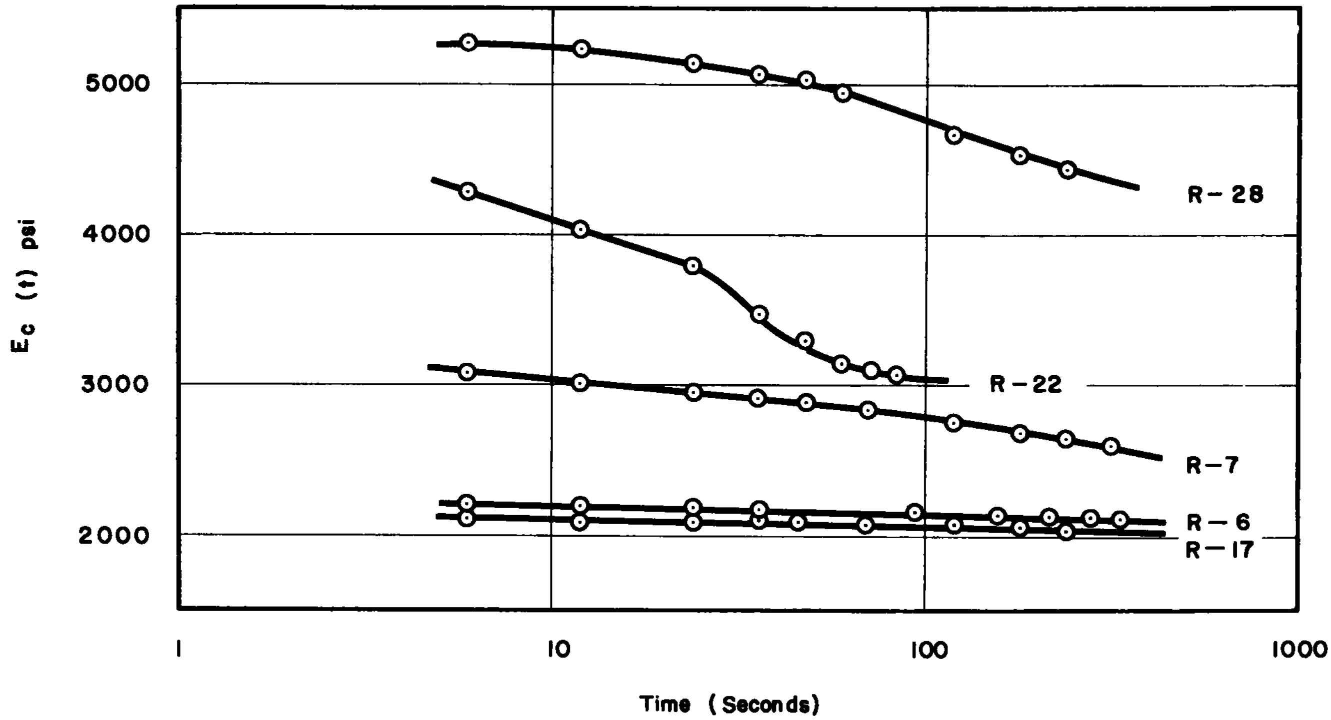

Figure 25. Creep modulus vs time for specimens compacted by P-7-B with unattached foot; five layers, 30 sec each, 1.86-lb added load.

comparable creep moduli. Of course, many more data and more thorough analysis are needed to substantiate this point.

Unconfined Compressive Strength

The unconfined compressive strength of the compacted specimens was determined according to ASTM D-2166-63T. Figures 12 and 26 show the effect of moisture content on unconfined compressive strength for specimens compacted by an air vibrator and by a P-7-B transducer with unattached foot, respectively. The upper curve in Figure 26 is for specimens compacted under 1.86-lb surcharge load. Figure 26 shows the unconfined compressive strength of the specimens whose moisture-density relationships are shown in Figure 16.

A comparison between Figures 16 and 26 shows that unconfined compressive strength of these specimens follows the same trend as does density. There is an initial decrease in strength as the moisture content increases, but a further increase in moisture content results in an increase in strength.

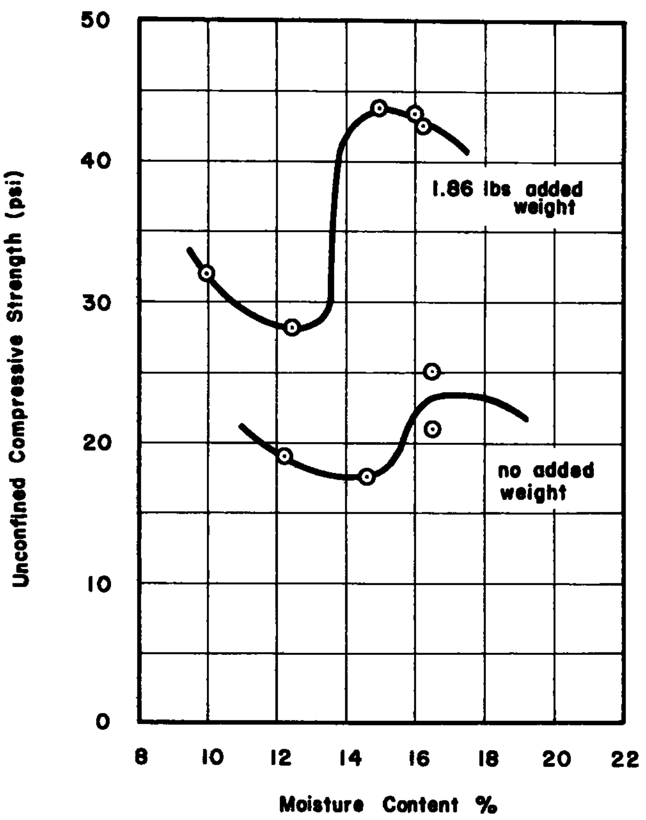

Figure 26. Unconfined compressive strength vs moisture content for specimens compacted by P-7-B with unattached foot; five layers, 30 sec each.

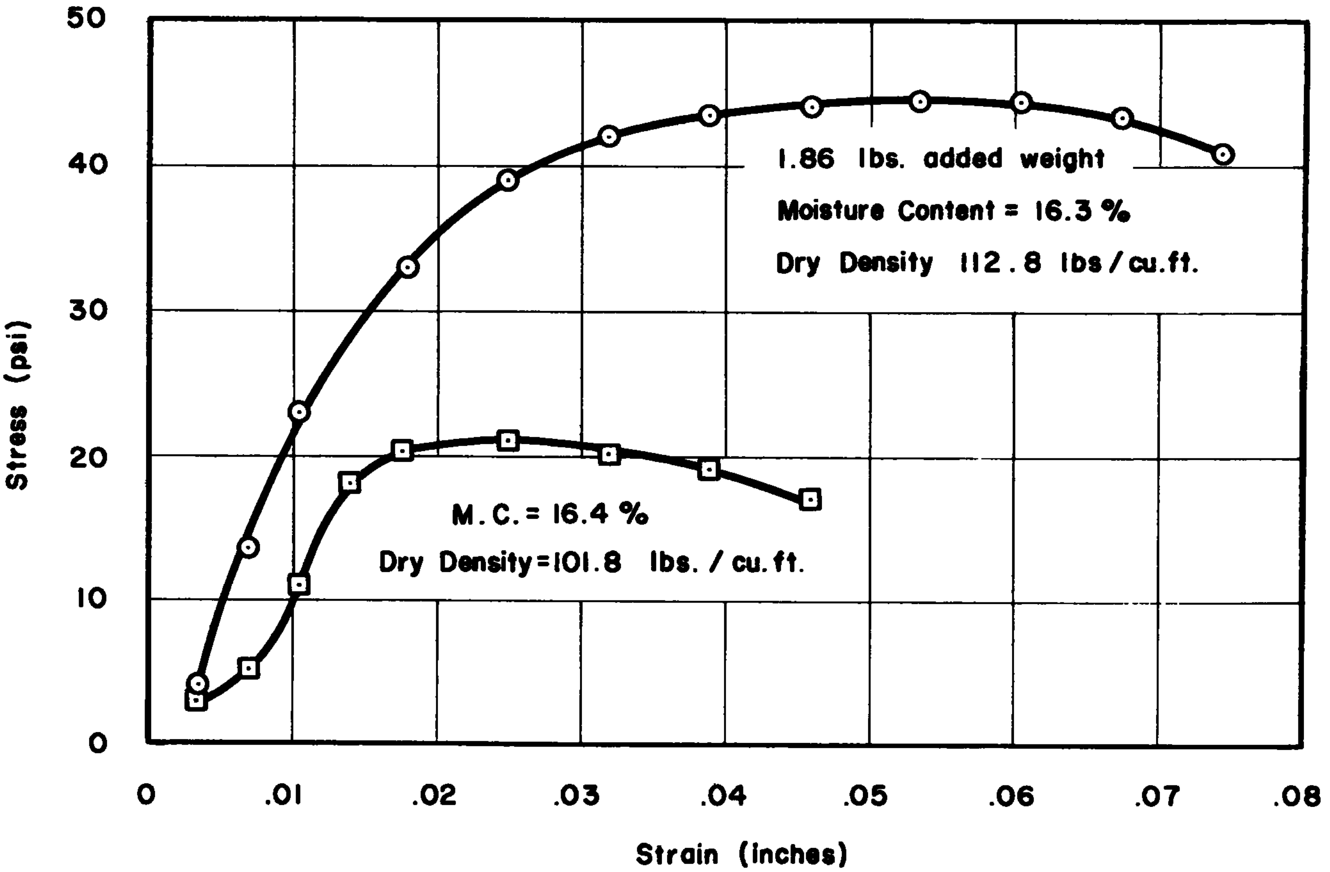

Figure 27. Stress-strain curve for specimens compacted by P-7-B with unattached foot; five layers, 30 sec each.

Figure 27 shows typical stress-strain curves for specimens compacted by P-7-B. The difference between the two specimens is in density, which was caused by addition of surcharge to one. These curves show that an increase of 1.86 lb in surcharge weight causes 10% increase in density, but the unconfined compressive strength is almost doubled.

COMPARATIVE RESULTS

To be able to compare the three methods of compaction directly, the following data are presented. These data were obtained using (a) the conventional Harvard miniature technique, (b) a low-frequency air vibrator Model BD-16, and (c) a high-frequency piezoelectric transducer Model P-7-B with unattached foot, with variation in the compactive effort for each method. That is, for the conventional Harvard miniature method two different spring constants (15 and 25 lb) were used; for the low-frequency BD-16 air vibrator two air pressures (30 and 60 psi, providing 8,500 and 11,750 vibrations per minute) were used; and for the high-frequency P-7-B transducer four different weights (surcharge of 0, 4.95, 12.83, and 27.86) were used. In all cases the P-7-B transducer was operated near the optimum tuned condition of 10.6 kcps.

Five batches of soil were prepared and mixed with five different moisture contents (Table 9). After mixing, each batch was divided into 200-gram portions and stored in sealed jars. Each specimen was compacted in five layers. For specimens compacted by the Harvard miniature technique each layer was given 25 tamps with the rammer of specified spring constant. For the rest of the specimens each layer was subjected to vibration for 1 min. Table 9 gives the results of moisture-density, unconfined compressive

TABLE 9

TEST RESULTS FOR COMPARISON OF DIFFERENT METHODS OF COMPACTION

TYPE OF COMPACTION	MOISTURE CONTENT (%)	DRY DENSITY (PCF)	UNCONFINED COMPR. STRENGTH (PSI)	CONSTANT STRESS USED FOR CREEP TEST (PSI)
Harvard miniature, spring constant = 15 lb	10.2	93.1	11.4	0.46
	13.0	89.6	17.0	0.46
	15.0	88.7	16.0	0.46
	17.5	91.5	7.8	0.46
	20.5	101.0	12.9	0.46
Harvard miniature, spring constant = 25 lb	10.2	92.3	12.8	0.46
	13.0	86.5	12.1	0.46
	15.0	90.7	17.5	0.46
	17.5	98.1	20.2	0.46
	20.5	105.0	16.4	0.46
Low-frequency air vibrator,[a] air pressure = 30 psi	10.2	91.0	7.1	0.93
	13.0	90.3	20.5	0.93
	15.0	93.5	16.2	0.93
	17.5	105.9	30.4	0.93
	20.5	106.3	17.5	0.93
Low-frequency air vibrator,[a] air pressure = 60 psi	10.2	91.5	7.8	0.46
	13.0	88.4	14.2	0.46
	15.0	93.2	13.4	0.46
	17.5	104.7	19.9	0.46
High-frequency piezoelectric transducer,[b] no surcharge	10.2	99.8	18.5	0.93
	13.0	99.7	31.5	0.93
	15.0	102.3	25.1	0.93
	17.5	108.9	27.7	0.93
	20.5	107.3	10.6	0.93
High-frequency piezoelectric transducer,[b] 4.95-lb surcharge	10.2	105.4	37.4	0.93
	13.0	106.5	46.6	0.93
	15.0	110.3	47.0	0.93
	17.5	113.8	37.7	0.93
	20.5	106.9	12.1	0.93
High-frequency piezoelectric transducer,[b] 12.83-lb surcharge	10.2	107.6	55.1	3.70
	13.0	111.1	70.7	3.70
	15.0	117.0	96.8	3.70
	17.5	113.8	45.3	3.70
	20.5	105.9	14.8	3.70
High-frequency piezoelectric transducer,[b] 27.86-lb surcharge	10.2	110.0	84.8	3.70
	13.0	113.7	97.1	3.70
	15.0	119.0	103.8	3.70
	17.5	113.7	44.7	3.70
	20.5	106.0	15.1	3.70

[a] Model BD-16. [b] Model P-7-B.

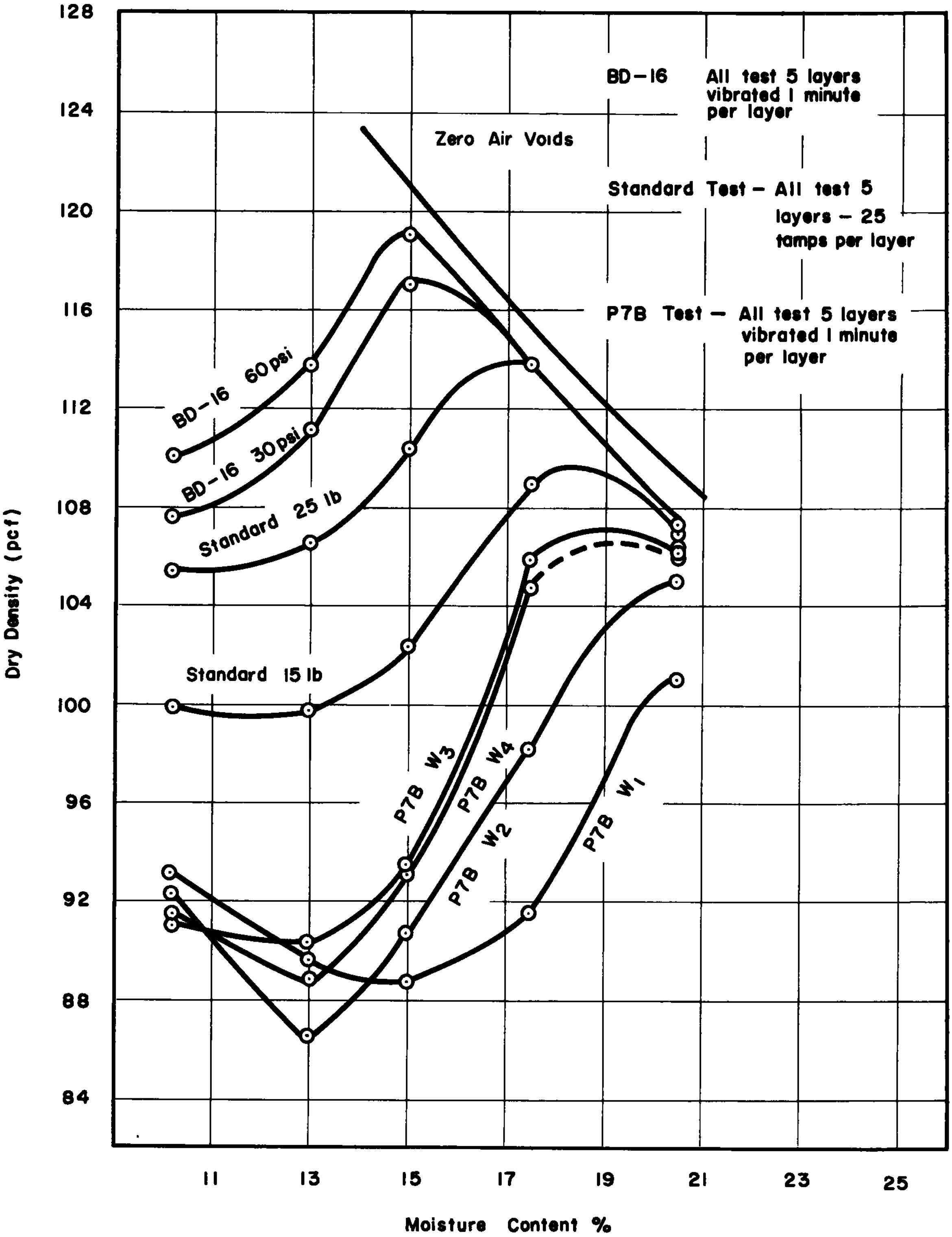

Figure 28. Moisture-density curves for different methods at different compactive efforts.

strength, and creep stress determinations on 40 different combinations used in this phase. Each value is an average of results from at least two identical tests.

Figure 28 shows the moisture-density curves for the eight different combinations, together with the zero air voids line for the soil used. For the compactive efforts used, the air vibrator produced the highest density at the lowest optimum moisture content. The high-frequency P-7-B transducer produced the lowest density at each moisture content used. At high moisture contents, due to stickiness of the soil, it was not possible to obtain meaningful results with P-7-B transducers; thus, no maximum density and/or

optimum moisture content could be established for this type of compaction. Similar to previous results, high-frequency compaction showed an initial decrease in density with increase in moisture content. Figure 28 also shows that when the specimens are compacted by vibration the slopes of their moisture-density curves are steeper than those for conventional curves. This, as discussed previously, means that the materials compacted by vibration may be-

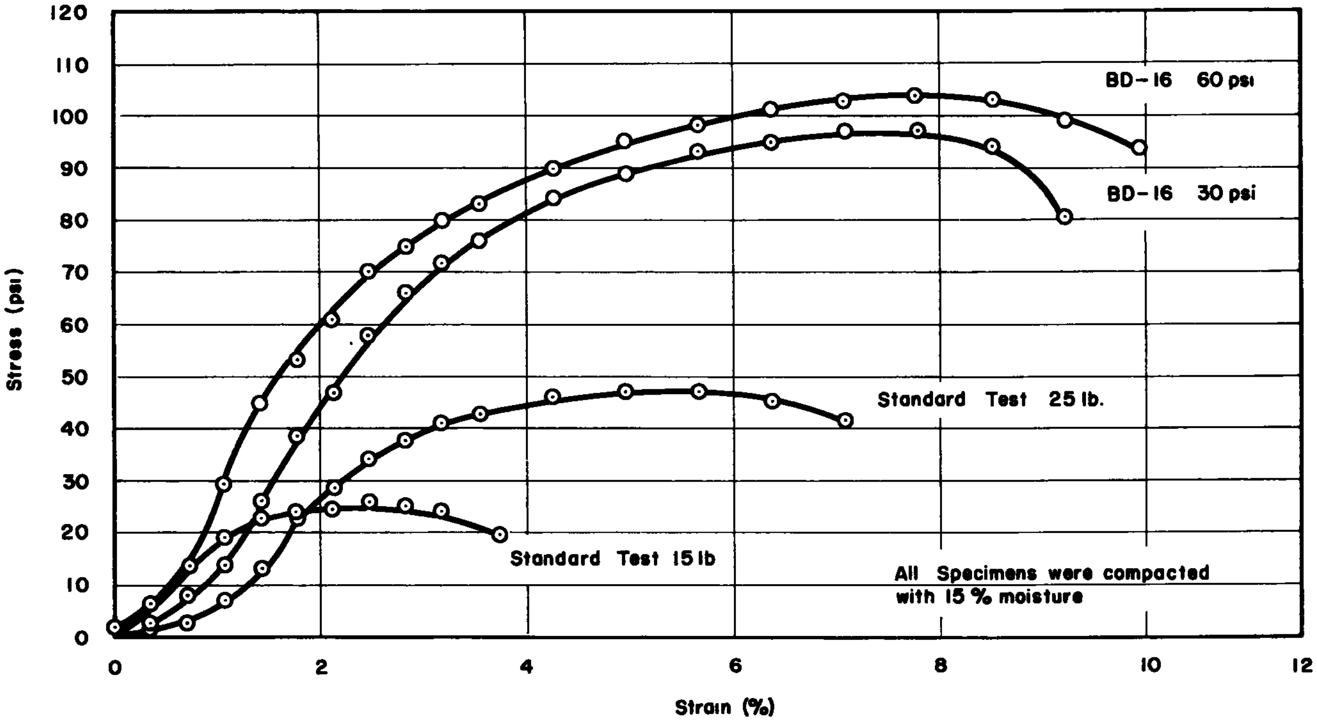

Figure 29. Stress-strain curves for specimens compacted by BD-16 and standard Harvard hammer.

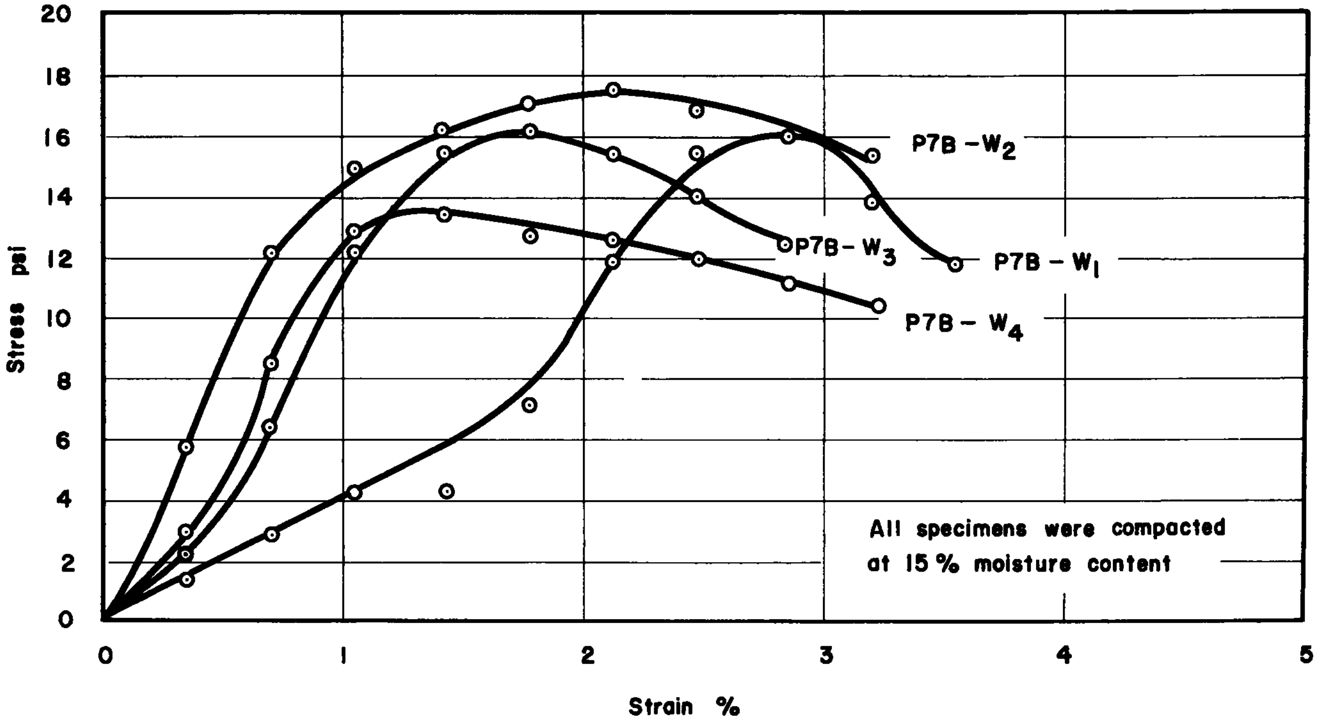

Figure 30. Stress-strain curves for specimens compacted by P-7-B with various surcharge weights.

come more sensitive to small changes in moisture content than those compacted conventionally in the laboratory.

Table 9, as well as Figure 28, shows that the static weight of the high-frequency vibrator has great influence on the density at high moisture contents. However, the results show that an increase in this weight increases the density up to a certain point, but further increase in static weight causes reduction in density. This indicates that in order for the maximum power to be transferred to the soil the vibrator should be under a certain amount of static load, the magnitude of which may depend on type of vibrator, frequency of vibration (especially resonance frequency), type of soil and its moisture content, and the connecting system.

In a parallel study on the use of P-7-B transducers for nail driving, it was found that for each frequency of vibration there is an optimum static pressure under which the nail is easily driven in a medium. For loads smaller than this optimum, the vibrator idles without any useful work; for loads greater than this optimum the energy is dissipated as heat, which results in melting of the nail or burning of the wood. However, this optimum static pressure was found to vary with frequency, type of medium (different kinds of wood or rocks), and the size and shape of the nail (the connecting system).

Figure 29 shows typical stress-strain curves obtained for specimens with 15% moisture content compacted with the BD-16 air vibrator and the conventional Harvard compactor. Figure 30 shows similar results for specimens compacted by a P-7-B transducer with different surcharge weights. Figure 31 shows the effect of moisture content of these specimens on their unconfined compressive strengths. For the air vibrator and the standard Harvard compactor the results are consistent and in general have trends similar to those of the moisture-density curves. Sensitivity of the specimens compacted by air vibrator to small change in moisture content is again obvious, a small change in moisture content causing a large change in unconfined compressive strength. Similar results for specimens compacted by a P-7-B transducer did not show any trend. However, the results show that although densities comparable to those of conventional methods can be obtained with the P-7-B transducer, the strength characteristics of these specimens are much lower than those compacted conventionally. Figures 32 and 33 show creep deformation versus time for specimens compacted with the BD-16 air vibrator, the conventional Harvard compactor, and the P-7-B transducer. Fig-

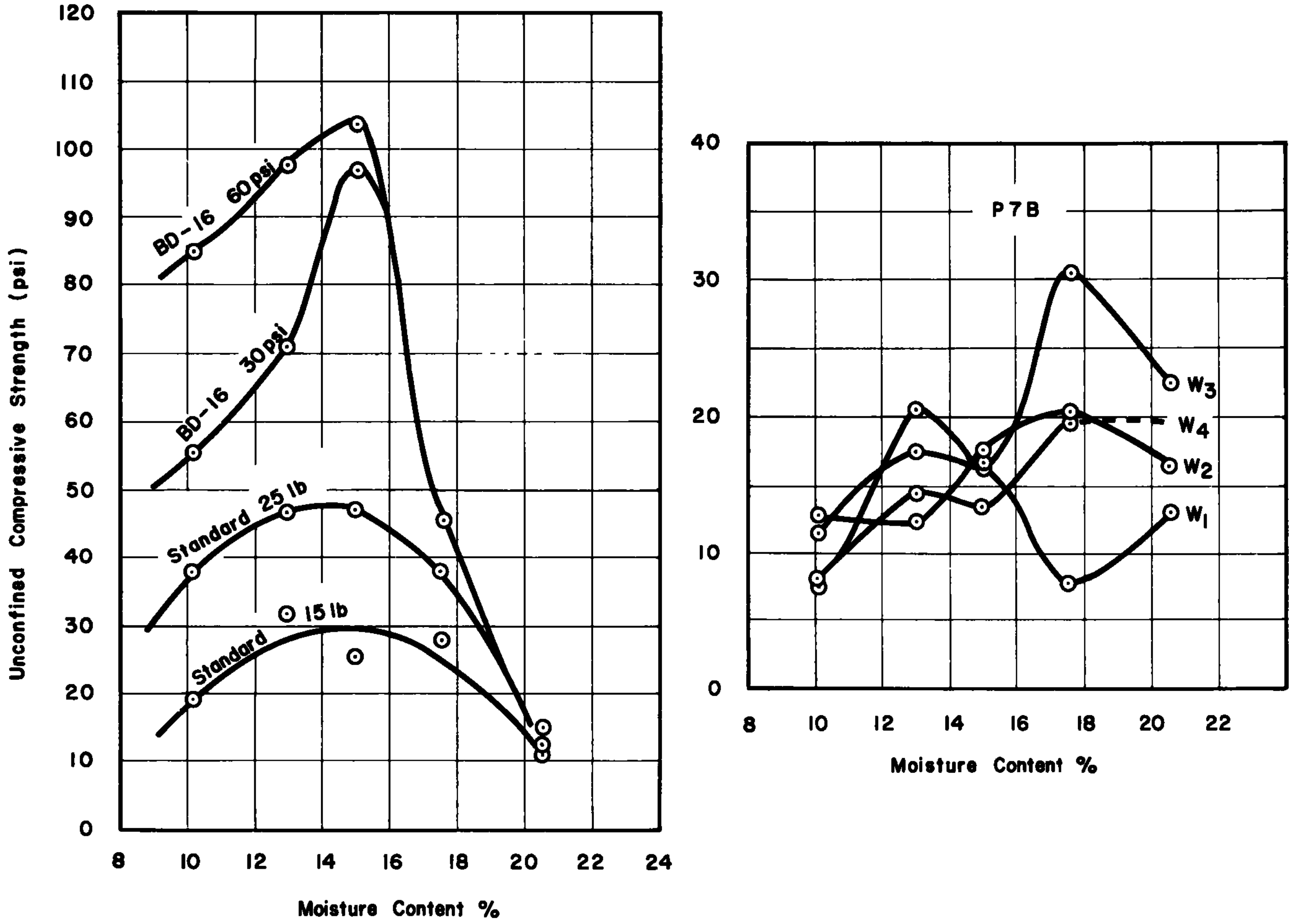

Figure 31. Unconfined compressive strength vs moisture content for specimens compacted by (left) standard and BD-16, and (right) P-7-B.

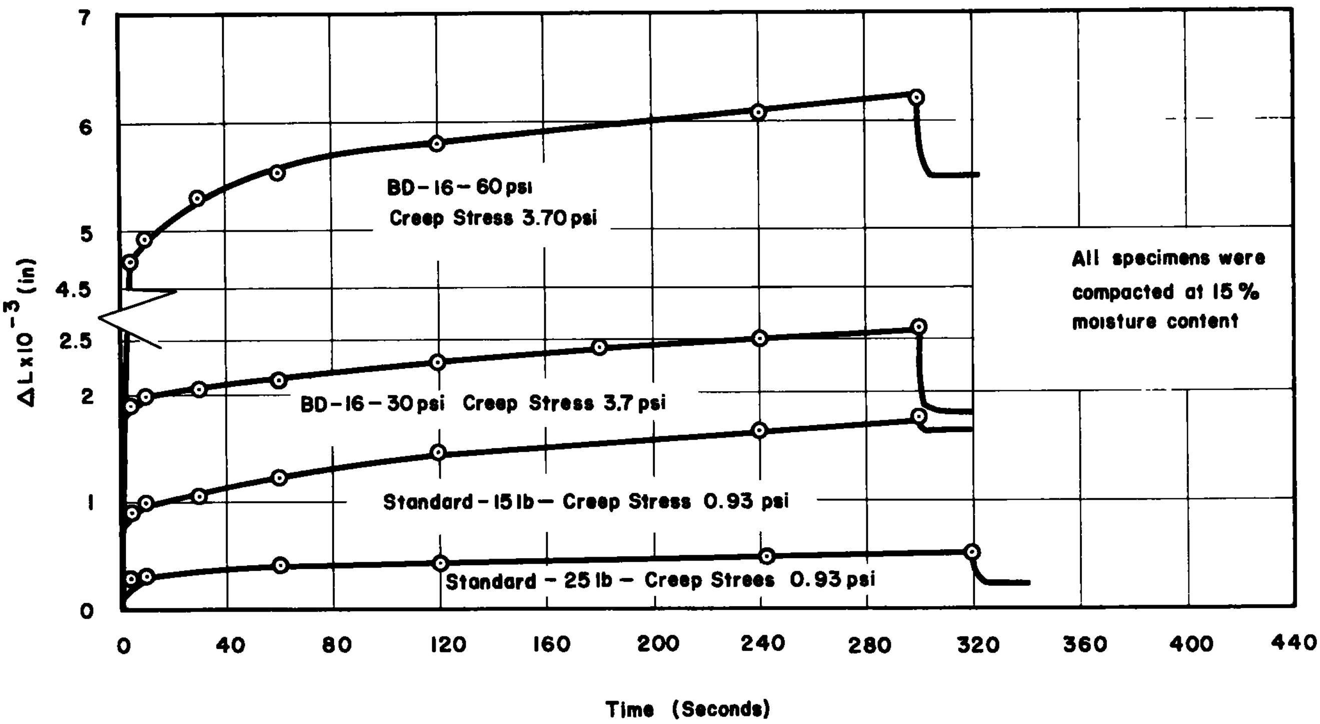

Figure 32. Deformation vs time for specimens compacted by BD-16 and Harvard hammer.

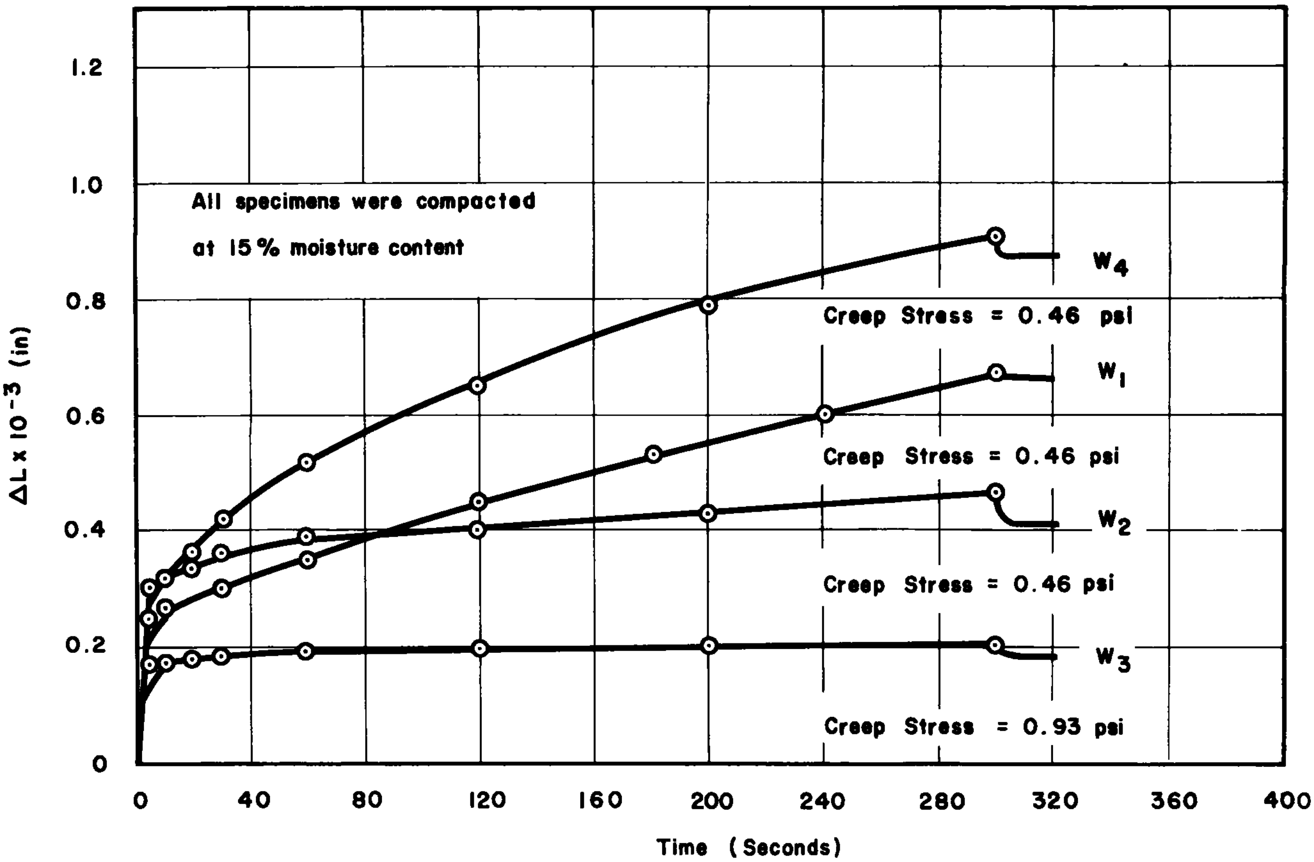

Figure 33. Deformation vs time for specimens compacted by P-7-B (see Table 9 for surcharge coding).

ures 34 and 35 show the variation of the creep moduli of these specimens with time, the specimens compacted by the high-frequency transducers having creep moduli similar to those of conventionally compacted specimens. This point is of interest, especially when considering that the P-7-B specimens had lower densities than conventionally compacted specimens.

It should be emphasized that the foregoing results with regard to soil vibratory compaction are only for one type of soil and most of the results are for specimens of 1⅜-in. diameter and 2⅞-in. height. In all cases the vibration was applied to the total area of each layer. Attempts were made to eliminate any contact between the vibrator foot and the mold. Generally, however, there were some contacts provided by soil particles, which caused some disturbance in direction and magnitude of vibration. Due to the size of the mold and the vibratory area, the wave reflections from the sides of the mold could not be avoided.

From the foregoing it is clear that vibratory compaction can produce changes in the strength properties of soils similar to those produced by conventional methods. However, much testing is required to determine the factors affecting vibratory compaction. Basically, the following three sets of variables should be studied:

1. Variables belonging to the vibrating system, such as amplitude, frequency, amplitude of force (whether constant or a function of frequency), and type of vibration (simple, applying only vertical displacement, or complex).

2. Variables belonging to the soil, such as initial density, resonant frequency, initial elastic constants, cohesiveness, and physicomechanical properties.

3. Variables belonging to the connecting system, such

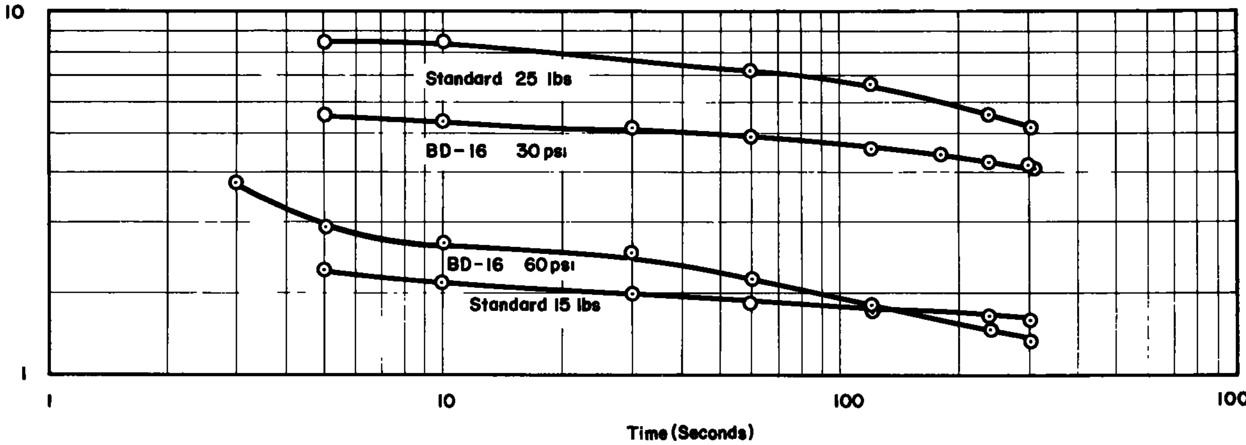

Figure 34. Creep modulus vs time for specimens compacted by BD-16 and Harvard hammer.

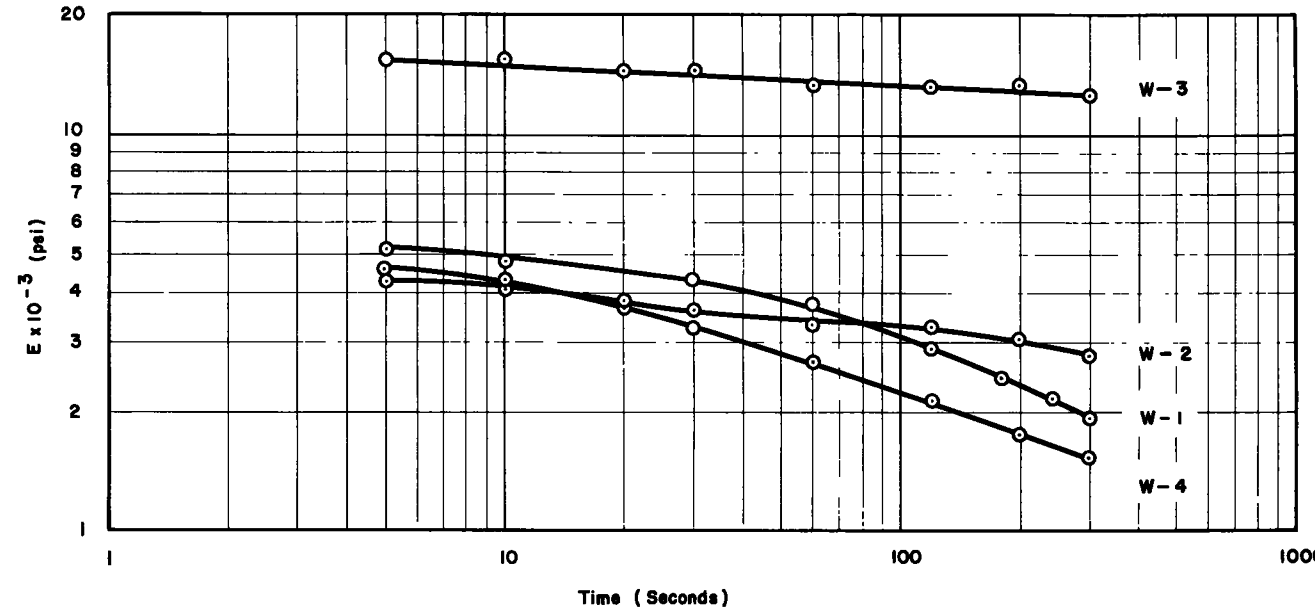

Figure 35. Creep modulus vs time for specimens compacted by P-7-B (see Table 9 for surcharge coding).

as impact vibration or attached vibration, size or shape of contact area between vibrator and soil, and degree of rigidity of the contact disc.

OTHER POTENTIAL AREAS INVESTIGATED

Other potential applications of sonic energy studied in this investigation included (a) vibratory compaction of asphaltic mixtures; (b) compaction of granular materials; (c) mixing soil and water; and (d) mixing sand, cement, and water. These attempts were not investigated in detail, mostly due to lack of funds and time, although some were discontinued due to lack of adequate instrumentation.

Mixing

Ultrasonic power levels applied to liquid media can cause these liquids to pass through small interstices of porous media at unusually high rates. These rates often exceed those possible by application of hydrostatic pressures, vacuum, or other techniques by orders of magnitude. This technique is successfully applied in the ceramic field, where blocks 6 in. thick are completely saturated with a fluid in less than 1 min. It was thought that this phenomenon might find some application in mixing of soil and water, and mixing of concrete.

TABLE 10

RESULTS OF SIEVE ANALYSIS OF RECOVERED AGGREGATE AND SPECIFICATION LIMITS FOR TYPE T-35-C BITUMINOUS CONCRETE

PASSING SIEVE	RETAINED ON SIEVE	SPECIFICATION LIMIT (%)		TESTING RESULT (%)
		MIN.	MAX.	
½ in.	⅜ in.	0	7	3.0
⅜ in.	No. 4	25	50	33.4
No. 4	No. 6	0	15	10.2
No. 6	No. 50	20	45	38.0
No. 50	No. 200	3	15	5.2
No. 200	—	0	8	3.2
Bitumen		4.5	9.5	7.00
Tot. retained on No. 6		40	65	46.6

Preliminary tests were conducted by placing uniform Ottawa sand in a transparent lucite container applying dyed water to the top of the sand, and noting the time required for the dyed water to reach the bottom of the container. It was found that the presence or the absence of sonic

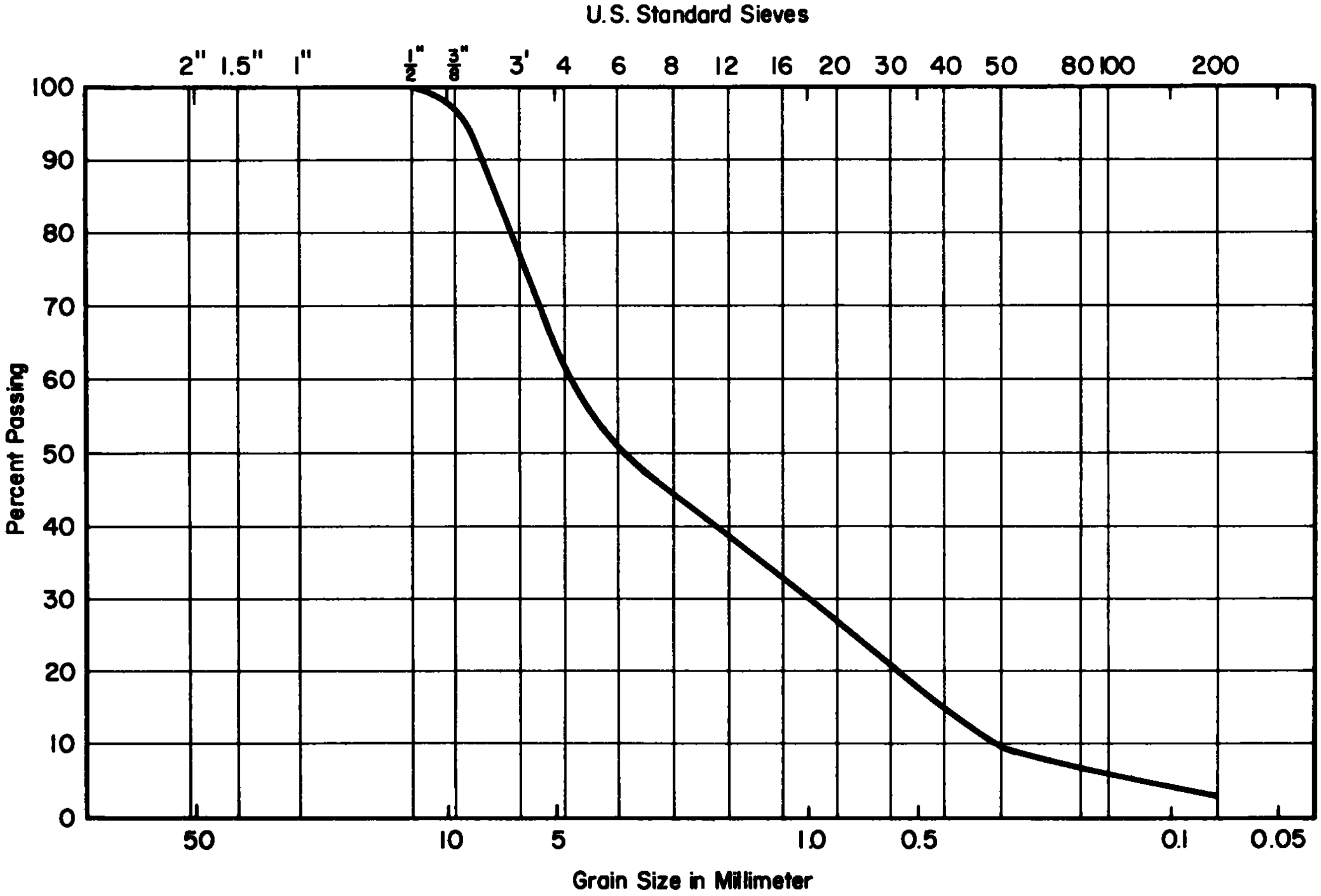

Figure 36. Sieve analysis of recovered aggregate of asphaltic mixture used.

TABLE 11

COMPACTIVE EFFORTS, STABILITY, FLOW, AND PERMEABILITY OF BITUMINOUS CONCRETE SPECIMENS

TYPE OF COMPACTION	SAMPLE NUMBER	COMPACTIVE EFFORT	BULK SPEC. GRAVITY	RELATIVE DENSITY (%)	MARSHALL STABILITY (LB)	MARSHALL FLOW (0.01 IN.)	PERME-ABILITY ($\times 10^{-8}$)
Marshall	A-1	20 blows each side	2.17	90.5	1,170	17	126
	A-2	40 blows each side	2.19	91.2	1,310	15	—
	A-3	60 blows each side	2.23	92.9	1,600	14	28.8
	A-4	80 blows each side	2.24	93.4	2,070	10	—
	A-5	100 blows each side	2.33	97	3,635	11	2.4
Static	B-2	4,000 psi	2.12	88.4	750	20	200
	B-3	6,000 psi	2.12	88.6	885	30	—
	B-5	10,000 psi	2.16	90	1,480	19	67.5
	B-6	8,000 psi	2.17	90.5	1,350	20	48.0
Vibration	C-9	2 layers, 1 min, 40 psi	2.12	88.4	1,175	24	—
	C-10	2 layers, 1 min, 40 psi	2.17	90.5	1,100	21	376
	C-11	3 layers, 1 min, 40 psi	2.17	90.5	1,290	22	253
	C-12	3 layers, 1½ min, 40 psi	2.19	91.0	1,390	23	274
Kneading [a]	D-1	20 strokes	2.15	89.5	500	—	107.5
	D-2	30 strokes	2.17	90.4	675	20	—
	D-3	40 strokes	2.19	91.3	914	20	47.1
	D-4	50 strokes	2.21	92.0	940	18	—
	D-5	60 strokes	2.22	92.5	1,120	17	8.9

[a] All specimens compacted under automatic operation with dwell time of 4 sec and foot pressure of 400 psi.

power on top of the layer of water did not make much difference in the rate of penetration. This incapability of sonic power to accelerate the penetration of water through the sand medium was attributed to the relatively large wavelength of sonic waves. For water to penetrate the soil medium at a faster rate, it is necessary that the energy applied be transferred in a wavelength smaller than the pore openings of the soil so that a wavelength can easily travel through the porous medium. Due to equipment limitations, the available transducers had wavelengths of the order of a few inches.

Transducers in the ultrasonic range (frequencies greater than 20,000 cps) are of very small power output, and until larger transducers of higher power levels are produced no significant conclusion can be drawn with regard to this application of sonic energy.

Compaction of Asphaltic Mixtures

The asphaltic mixture used for this preliminary study was an asphaltic concrete for a surface course. This mixture was prepared by a local commercial asphalt plant according to Ohio State Highway Department specifications for Type T-35-C asphaltic concrete. The composition specification of this mixture, together with the results of extraction and gradation analysis of a representative sample, is given in Table 10. Figure 36 shows the gradation of the recovered aggregate.

For this mixture an attempt was made to compare the results of vibratory compaction with those of Marshall hammer, static, and kneading compaction. Table 11 gives the compaction effort used for each specimen, as well as the resulting relative density, Marshall stability, Marshall flow, and permeability. Figure 37 shows a typical plot of Marshall stability versus relative density of the samples. Figure 38 shows similar results for the permeability of the specimens. Relative density of the specimens was determined as the ratio of bulk density of the specimens to the maximum density of the mixture as determined by Rice's method of maximum specific gravity. The specimens were all 4 in. in diameter and 2.4 to 2.6 in. in height. The Marshall stability and flow values were determined according to Asphalt Institute procedures. The vibrator used for this phase was an air vibrator Model BD-25.

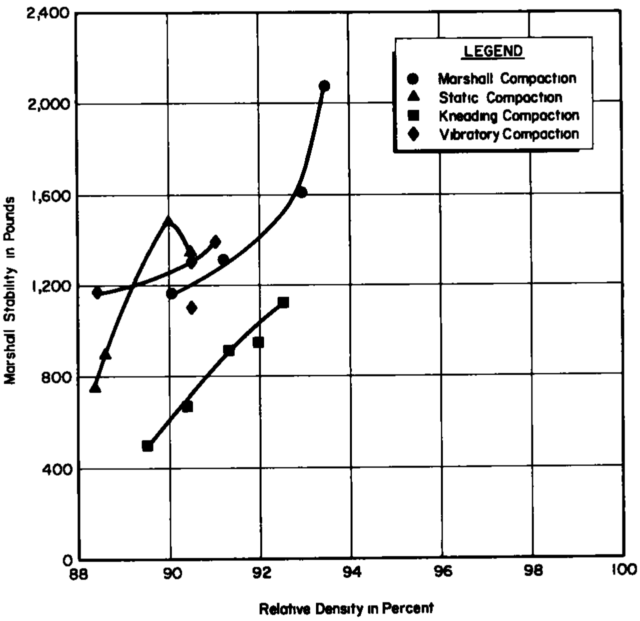

Figure 37. Relative density vs Marshall stability for various methods of compaction.

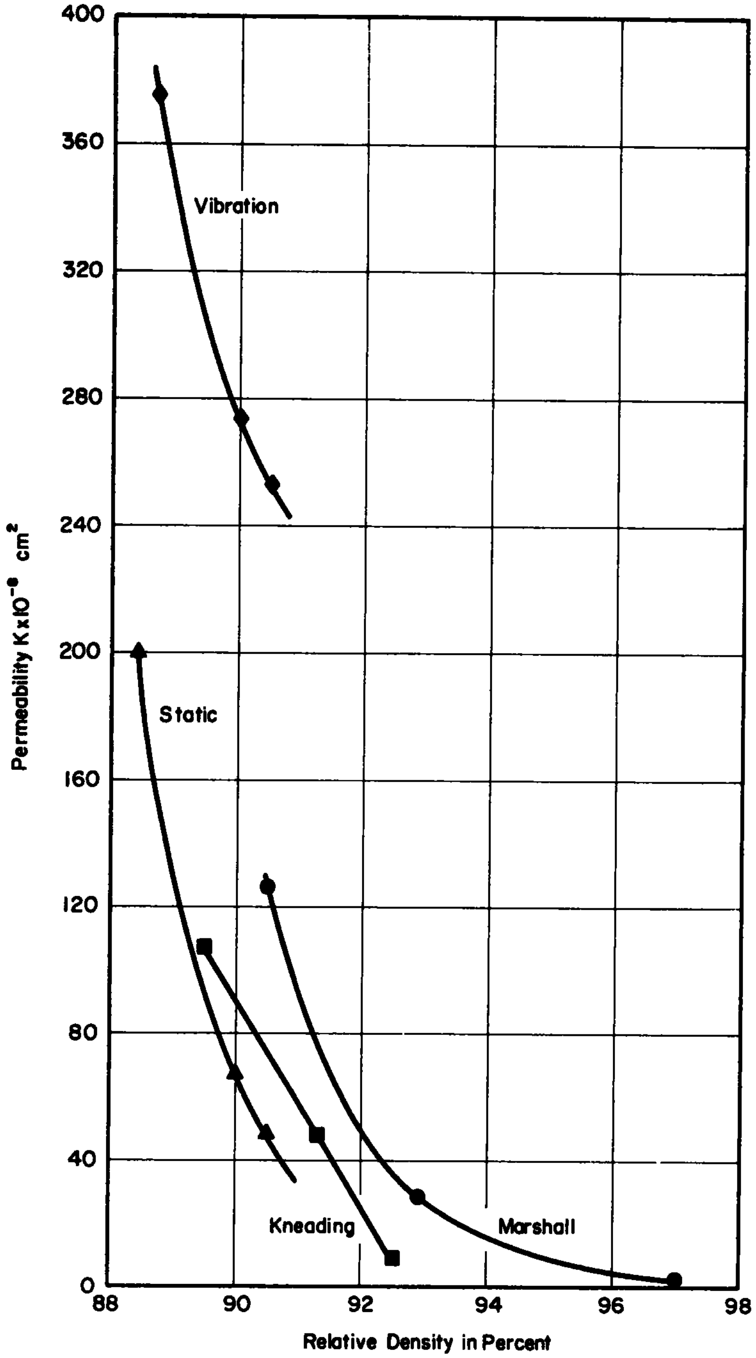

Figure 38. Relative density vs permeability for various methods of compaction.

This phase of the study was abandoned because (a) due to the small power output of available piezoelectric transducers no significant results could be obtained by their use, and (b) the low-frequency air vibrators did not have a good repeatability because of cooling of the specimens. Approximately 15 min was required to assemble a sample for vibration and a few minutes for compaction. Although attempts were made to provide heat through infrared lights, it was found that a more positive control system was needed.

Compaction of Granular Soils

A limited number of tests were performed to study the vibratory compaction of sands. For this purpose an Ottawa sand (ASTM-C-109) was used in 4-in. diameter steel molds placed in the vibration table. The vertical displacement of the surface of the sand was measured intermittently. The vibration table shown in Figure 8 was designed in such a way that it was possible to apply the following vibrations to the specimens: (a) vertical vibration from the bottom,

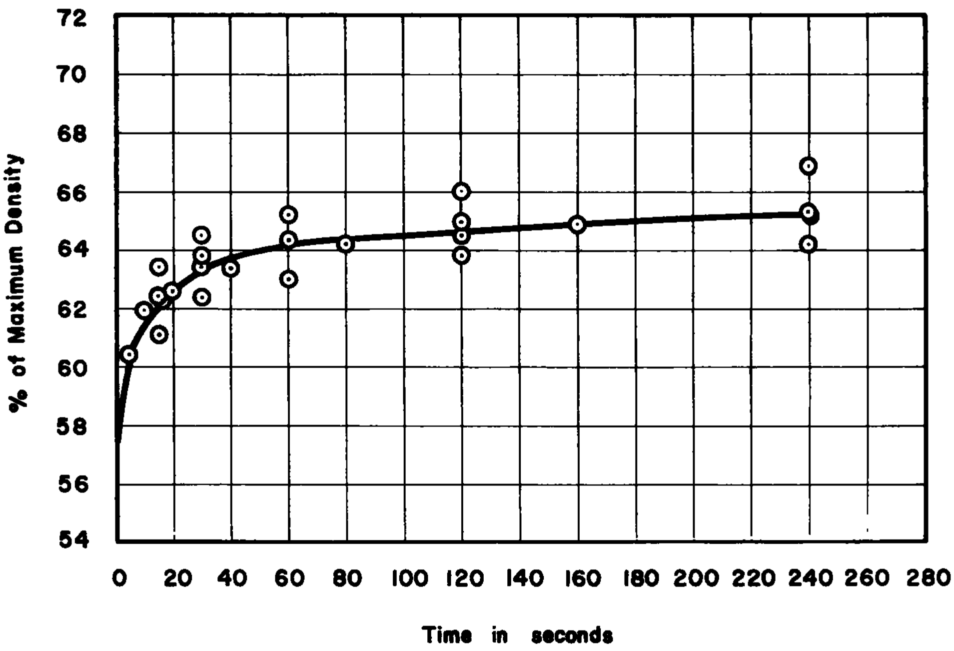

Figure 39. Change in density vs vibration time for a sand sample (four specimens).

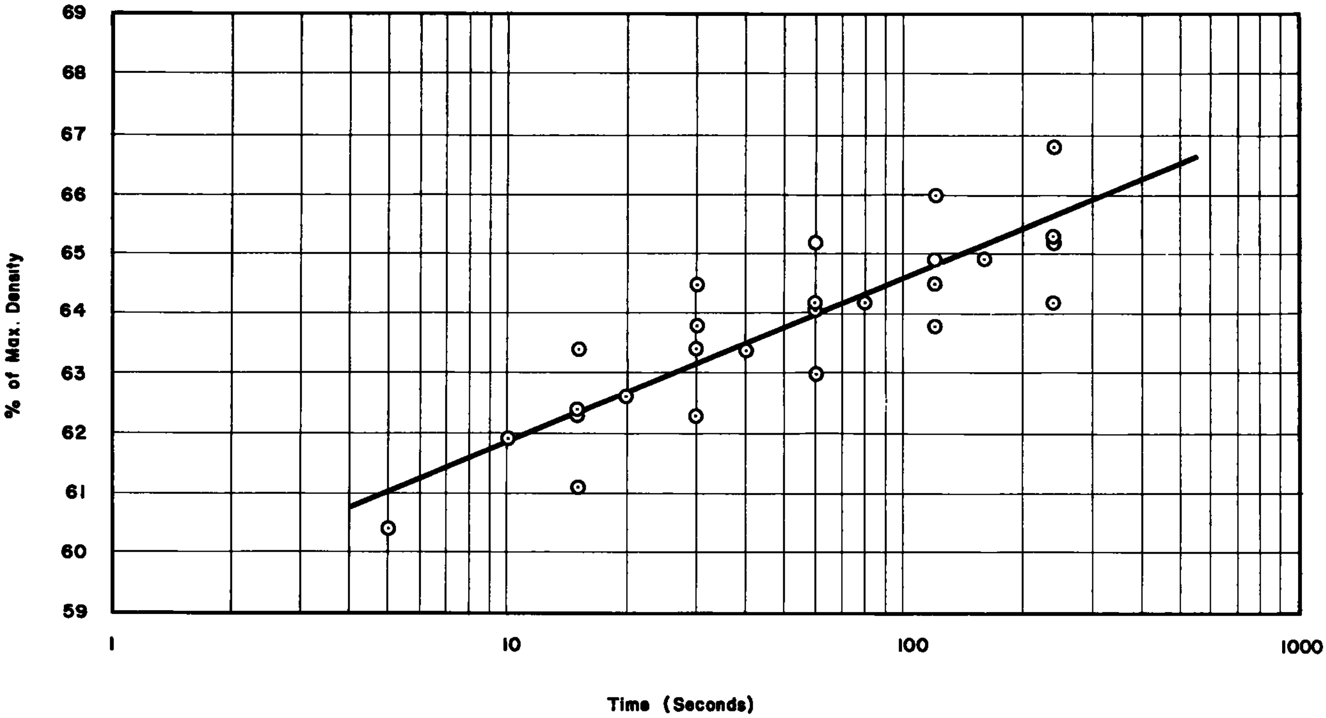

Figure 40. Change in density vs vibration time for same sand sample (four specimens) as in Figure 39.

top, or a combination of the two; (b) horizontal vibration from the bottom; (c) a combination of (a) and (b); and (d) vibration under different dead loads. Substitution of vibrators made it possible to achieve numerous combinations.

A typical result of change in density of the sand versus vibration time is shown in Figure 39, in which the curve represents the average of four specimens. These same results plotted on a semi-log scale generated a straight line as shown in Figure 40. The scatter of the data is mostly due to the device used to measure the settlement of the sample surface. An automatic recording device would probably have given more accurate results.

CHAPTER FIVE

POTENTIAL APPLICATION OF SONIC VIBRATION TO HIGHWAY CONSTRUCTION

Sonic vibrations can cause many potentially useful effects, as well as possible undesired effects. Sonic engineering is the science of attaining effective levels of the desired effects, without encountering deleterious levels of undesired effects. The choice depends on the application, and the nature of the effects desired. Each application can require careful engineering design, based on a thorough knowledge of the nature of sonic generation and transmission systems, and the nature of the physical effects of sonic energy in engineering materials.

IMPACT PILE DRIVING AND IMPACT FORCES

The ability of sonic power systems to provide rapid repetition of high force levels permits the use of ultrasonic energy to provide repeated impact blows of high magnitudes. For this type of application transducer and coupling systems are designed to lift the impact tool away from contact with the work material, and then to accelerate the tool into impact with the material, many hundreds or thousands of times per second. Static force, of magnitude less than the peak dynamic force, can be added if needed. Such systems of impact pile driving, drilling, or shaping offer special advantages in the case of hard materials that deflect very little and tend to fracture upon impact. Sonic impact drills have been developed, using magnetostrictive transducers, for broad ranges of force levels. A small unit, about the size of a fountain pen and operating at 40 watts at near 40,000 cps, was developed for drilling teeth. Similar units, operating at about 100 w, have been used to drill holes in plate glass or hard ceramics. One of the largest units fabricated to date delivered about 100,000 lb of dynamic force, at near 100 hp, for drilling oil wells in hard formations. This unit, 42 ft long and only 8 in. in diameter, operated at low sonic frequencies, and drilled in limestone formations at about five times the speed of large rotary drills commonly used in drilling oil wells. Intermediate sizes, possibly in the range from 5 to 10 hp, might possibly be developed, if justified for drilling or cutting of concrete pavements, or for drilling blast holes in hard rock formations.

MEASUREMENT OF MATERIAL PROPERTIES AND DIMENSIONS

Extensive use is made of sonic and ultrasonic methods of nondestructive testing of materials. This is a highly refined method for metals and permits ready detection of discontinuities as small as $\frac{1}{64}$ in. in diameter, even when these are thin oxide or other laminar flaws of very small thicknesses. In wrought metallic materials (such as steel and aluminum) with very fine grain sizes, ultrasonic waves can be readily propagated through great thicknesses (such as 50 ft or more) of material. Useful echoes can be returned from defects to permit their location, evaluation, and repair or rejection if justified.

Unfortunately, with composite materials such as concrete and other highway pavement materials containing aggregates, discontinuities exist at each interface between aggregate and binder. The sensitivity of sonic and ultrasonic tests to variations in material properties is so great that numerous echoes are returned from these interfaces, unless the ultrasonic wavelength is made larger than the reflector areas. In addition, the velocity of sonic waves varies with material density ρ and modulus E, since

$$v \propto \sqrt{E/\rho}$$

with longitudinal waves. Extensive tests of ultrasonic measurements in concrete in England and Canada, as well as in the United States, show that density variations in concrete are significant in magnitude. Longitudinal sound wave velocities can vary from as low as 7,000 to more than 15,000 ft/sec in thick concrete structures. In general, the strength of the concrete appears to be greater in samples with higher sonic wave velocities. However, the variation in sonic velocities tends to complicate the measurement of thickness or depth of discontinuities in terms of the transit times for wave reflections.

REDUCTION OF FRICTION

High dynamic mechanical force levels can be used to offset the effects of high static forces in contact friction. To attain this effect, the dynamic force peaks must exceed the static force level. During the retraction part of the dynamic (alternating) force cycle, the sonic force lifts the mating surfaces out of contact. During this brief interval, sliding friction is eliminated. Relative motion occurs with small tangentially applied force. With many hundreds or thousands of cycles per second, during each of which the contacting surfaces are separated temporarily, sliding friction is greatly reduced. Elastic displacements may occur during the brief intervals of contact, permitting an apparently continuous motion.

Such systems could perhaps be developed into continuously adjustable brakes or clutches for heavy earthmoving or highway construction equipment. Upon de-energization, the brake or clutch assures positive clamping, because of the high static forces applied. Such effects might also be used

to alleviate friction in extrusion presses or dies, by alternately releasing and applying clamping pressure upon the material being extruded or deformed.

Other uses of this effect in highway construction could be for ice and snow removal equipment. Pilot studies for application of vibration to the blade of a snow plow have shown some promising results. It is found that, in general, vibration of the blade provides some reduction in friction and causes the blade to carry more snow than is the case without vibration.

PUMPING OF LIQUIDS THROUGH POROUS MEDIA

Accelerating the rate of penetration of liquids into porous media such as subgrade soil, subbase and base, and surface layers of highways has some important applications in highway construction. These may include:

1. Forcing stabilizing materials into porous or soft soil formations beneath highways.
2. Pumping cement slurries or concrete mixes through soft crushed rock or other aggregate materials during construction.
3. Pumping pigments or other markers into porous pavement materials, to designate lanes or safety markers.
4. Repairing cracked concrete pavements or repairing weather damage.
5. Controlling application of bituminous materials to crushed rock subcourses, to ensure penetration to desired depths.

OTHER SUGGESTED POSSIBILITIES

Some of the possible applications of sonic energy which may be useful to the highway industry are as follows:

1. Ultrasonic pumping.
2. Ultrasonic acceleration or control of chemical reactions.
3. Ultrasonic mixing or dispersion.
4. Ultrasonic grinding.
5. Ultrasonic cutting, drilling, carving.
6. Ultrasonic reduction of friction.
7. Ultrasonic control of friction.
8. Magnetostrictive actuators for servo and control systems.
9. Ultrasonic degassing and deairing.
10. Ultrasonic dispersion of chemicals.
11. Ultrasonic welding of sheet materials.
12. Ultrasonic cleaning.
13. Ultrasonic soldering, brazing, tinning, and metal coating.
14. Atomization.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

In summary, this investigation of potential uses of sonic and ultrasonic devices in highway construction has resulted in an extensive survey of the literature on past developments in the field of sonic and ultrasonic research and applications of vibratory energy in civil engineering applications. In general, these literature references fall into two basic classes: (a) evaluations of low-frequency vibration systems with civil engineering applications, and (b) research with low-power high-frequency vibration systems which were generally not applicable to civil engineering applications. In both instances, the beneficial effects of sonic energy in soil compaction and other highway engineering applications have been minimal because the sonic power levels were quite inadequate for the basic functions required in highway engineering applications. (Sonic power requires both high force amplitudes and high audio frequencies if high power levels (several horsepower) are to be provided to the work materials.) Thus, although many possible beneficial effects can be demonstrated by low-power experiments, the magnitudes of these benefits remain too low to be attractive in practical applications.

In this preliminary research investigation, conducted with sonic transducer and vibration-excitation systems available during the research period, similar limitations existed. The true levels of sonic power provided to the work materials in these tests were typically in the range from 10 to 100 watts. This level of sonic power was so low that beneficial effects of sonic power were very small in comparison with the natural properties of materials and the beneficial effects of high static loads used with conventional methods. (These sonic power levels were often hardly greater than those attained by patting the work materials with the human hand.) Despite these power limitations, some significant effects were observed, but the magnitudes of these effects were minimal. Tests included standard and vibratory compaction of highway materials, especially soils, and limited tests on mixing and compaction of other highway materials such as asphaltic mixtures and granular materials.

Development of High-Power Sonic Transducer Systems

Since the completion of the study described in this report, research activities in the Ultrasonic Power Laboratory of The Ohio State University, under sponsorship of the Ohio Department of Highways and the U. S. Bureau of Public Roads, have made major strides in development of practical high-power sonic transducers (*1, 11, 12*).

Low-frequency high-force transducer systems have been

developed to apply forces up to 6,000 lb at frequencies in the range of 60 cps. These have been demonstrated as remarkably effective in increasing the capacity of earth and snow removal by tests on small (garden-type) tractors. For example, with at 42-in. blade, a 2½-hp garden tractor was stalled by less than 1 in. of many soils. With the high-force transducers applied to the 42-in. blade, the tractor moved at its highest speed with the blade completely filled with earth.

Similar experiments with a full-scale farm tractor pulling a multi-blade plow in clay-type soil indicated that the tractor could move in its highest-speed gear with much deeper penetration of the vibrated plow blades, whereas without vibration a low-speed gear and much less blade penetration was required to obtain plowing action. In addition, in this case, the soil was broken up effectively by the vibrational action, resulting in beneficial effects equivalent to those obtained by subsequent harrowing or other treatments.

Similar benefits of high-force low-frequency vibration were also demonstrated in removal of snow and ice from pavements. With snow and ice compacted by traffic after a severe snow storm, the 2½-hp garden tractor with 42-in. blade was totally stalled by 1 or 2 in. of compacted ice and snow, without blade vibration. Even after a running start of 10 ft on bare pavement, the tractor stalled on impact of the blade on the packed snow. On the other hand, with the high-force vibrator applied to the 42-in. blade this small tractor could start from standstill with 6 to 10 in. of packed snow and ice, and move readily through such packed snow at its full speed of travel, with the blade filled with snow.

Similar remarkable improvements have also been demonstrated by application of high-force, 60-cps vibration exciters to tasks such as post driving and removal, where penetration rates of the order of 1 ft per minute have been attained with simple high-force vibration systems attached to the top of the post being driven. In each of these cases application of an adequate level of power has resulted in improvement of performance by an order of magnitude over results obtained without vibration.

In addition, preliminary tests with portland cement concrete indicated that sonic mixing and placement of relatively dry mixes resulted in doubling the compressive strength of cylindrical test specimens after seven days of curing, and a final strength improvement (after 28 days) of 25%. These tests, made with relatively low transducer forces in a crude vibration application apparatus, indicate a potential benefit of great economic significance in highway engineering. With advanced transducer systems now available, it is probable that further improvement in properties could be attained.

Parallel development of high-power high-frequency (10,000 cps) piezoelectric transducers has shown equally remarkable results in this more recent research. Sonic motors (similar in design to those shown in Fig. 3) have now been developed to provide 15 hp of output with better than 95% power efficiency. These units generate more than 2 hp per cubic inch of piezoelectric material (an unusual power density for electromechanical motors). The attached steel force-concentration members can readily provide output force densities exceeding the yield points of structural steels (30,000 to 45,000 psi).

Such sonic power levels are adequate to heat steel bars rapidly (by plastic deformation and cycling at stress levels exceeding the elastic limit). When a ⅜-in. diameter steel tensile test bar is attached to the end of one of these transducers (operating at only 20% of its power capacity), the gage section is heated to 725 F (blue temper colors) in only 7 sec. In 15 sec the center of the gage section (where maximum sonic stress exists) is brought to a bright red heat. In less than 30 sec, the tensile bar can be fractured.

These tests provide a remarkable demonstration of the effects of high sonic power levels upon materials. In their present stage of development these sonic motors surpass conventional electric and internal combustion motors in every basic operating characteristic. Size, cost, and maintenance are greatly reduced because the units have no moving parts and are extremely rugged. Power outputs per unit weight or volume, and efficiency, far exceed those of comparable conventional driving systems. Any number of these 15-hp units could be driven in parallel to provide sonic power outputs in the range from tens to hundreds of horsepower. There is no evident reason why still higher power outputs could not be obtained from larger single units of this basic type.

In comparison with the sonic exciters used in the experimental work described in this report (providing power outputs of a few pounds of force at low frequency, and power outputs of less than 100 watts at high frequencies), the newly developed sonic exciters provide output power and force gains of more than 1,000 times. With such transducers it is evident that the small beneficial effects due to vibration reported in these preliminary tests could be vastly enhanced. An intensive study with high-output sonic devices is urgently needed to supplement this early investigation.

CONCLUSIONS BASED ON PRESENT STAGES OF DEVELOPMENT

From (a) the results of preliminary tests of effects of sonic vibrations on highway materials at the low power levels available during this investigation, and (b) the present availability of sonic power systems capable of 1,000 times higher power or force outputs, it is evident that:

1. Sonic energy can provide significant potential benefits in highway engineering and construction systems, and in earth moving, hole drilling, soil compaction, mixing and placement of materials, and improvement of properties of roadway surface layers, subgrade, and base materials, when adequate power levels are available to achieve the desired results.

2. To attain the potential benefits of high-power sonic systems in highway engineering, more fundamental information is required on the dynamic behavior of highway materials under high-force vibration, particularly with nonhomogeneous media such as soils and concrete. Basic studies are required with high-force and high-power vibratory systems upon many materials used in highway construction.

3. Research should be conducted with high-force high-

power sonic systems especially engineered to provide maximum force and energy transfer to highway materials for evaluation of effects in compaction, densification, strengthening, and movement, in controlled laboratory tests providing quantitative data useful for highway design, materials selection, and improvement of construction practices.

4. Upon proof of optimum effect in laboratory studies on highway materials, research should be extended to field tests on highway construction sites, with larger-scale test equipment and totally adequate power and force levels of sonic vibration. Complete instrumentation of sonic energy application systems, and of materials response characteristics, should be included in such field tests, to provide quantitative data that can be correlated with prior laboratory test results.

5. Upon demonstration of large-scale effectiveness of high-power sonic vibration systems in highway engineering operations, engineering development should continue in cooperation with manufacturers and users of large highway construction equipment, to adapt these systems for use of vibrational systems to increase productivity, speed of operation, efficiency of performance, and capacity for work. Inasmuch as sonic systems must be engineered to basic principles and high precision to attain optimum results, skilled sonic engineers and designers should take a major responsibility in these development operations.

RECOMMENDATIONS FOR FUTURE DEVELOPMENT

It is highly recommended that the basic research objectives cited for this preliminary program be achieved by use of high-power high-force sonic systems adequate for the task, and that the work be extended to full-scale test and field operating conditions. Such high-power sonic systems did not exist and could not be procured from any source at the time of this preliminary investigation (1964). At present (1966), such sources have been developed to a high degree of reliability, practicality, and ruggedness, and could be used to provide power levels from 10 to 100 hp. Such sources are absolutely essential to the successful achievement of compaction, strengthening, and efficient movement of earth, rocks, and highway construction materials.

It is further recommended that such full-power sonic research be fully implemented with adequate support to permit construction and use of heavy-duty systems required for continuous operation at high vibratory force levels. All needed components of the sonic power application systems must be provided, including:

1. High-power high-frequency electrical generators, such as are used in induction heating in industry.

2. High-voltage high-frequency power transformers (proven practical and now commercially available through developments in the sonic power research at The Ohio State University).

3. High-power and high-force sonic motor or transducer systems (now developed and proven practical through the same University research activity).

4. Rugged vibratory force transmission and coupling systems to connect such motors to tools and blades used in highway engineering (basic threaded systems have been proved effective in the present research work).

5. Special tools and force application systems must be designed to meet the optimum requirements of coupling and working on highway materials. (These do not presently exist, and will require intensive basic engineering development to permit high-power operation without material fatigue and erosion failures.)

Because of the large-scale power operations involved, it is evident that an adequately funded program with a minimum of three years duration will be required to attain the basic objectives of complete laboratory tests, field tests, and reduction to practice in large-scale highway engineering operations. Such developments are now technically feasible, whereas they might have been considered impossible during the period of this initial investigation three years ago.

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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 Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.