NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **168**

RAPID MEASUREMENT OF CONCRETE PAVEMENT THICKNESS AND REINFORCEMENT LOCATION

FIELD EVALUATION OF NONDESTRUCTIVE SYSTEMS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RAPID MEASUREMENT OF CONCRETE PAVEMENT THICKNESS AND REINFORCEMENT LOCATION

FIELD EVALUATION OF NONDESTRUCTIVE SYSTEMS

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HARRISBURG, PENNSYLVANIA

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

AREAS OF INTEREST:
- PAVEMENT DESIGN
- PAVEMENT PERFORMANCE
- CONSTRUCTION
- GENERAL MATERIALS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1976

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP Report 168

Project 10-8 FY '70
ISBN 0-309-02508-7
L. C. Catalog Card No. 76-28564

Price: $4.80

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National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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Printed in the United States of America.

FOREWORD

By Staff
Transportation Research Board

Highway construction and materials engineers, researchers, testing equipment manufacturers, and others who may be concerned with the control of concrete paving operations will find this report to be of interest. It has resulted from a study that included a comprehensive state-of-the-art survey followed by extensive field development and evaluation of nondestructive testing techniques for the determination of portland cement concrete pavement thickness and reinforcement position. The work was limited to the use of existing nondestructive testing equipment. Measurement techniques developed during the investigation are described in sufficient detail for potential users to investigate further the usefulness in their own situations. Sufficient information also is presented to assist prospective manufacturers of the testing equipment to determine needed improvements.

The survival of portland cement concrete pavements is strongly related to thickness. This has long been recognized, as indicated by the severity of the penalties that historically have been assessed against paving contractors for thin sections. The importance of thickness also was demonstrated effectively in the AASHO Road Test.

Many thousands of measurements are made each year to assure that the thicknesses of newly constructed concrete pavements are in compliance with those specified. For pavements in which steel reinforcement is used, the position of the steel must be similarly determined. Cores taken from the hardened concrete, usually at the rate of one per 1,000 lane-feet, figure prominently in the measurement process. Unfortunately, coring is time consuming, costly, a cause of troublesome discontinuities, and of no value in thickness control during the construction process.

Highway engineers have been attracted for many years by the possibility that most or all of these disadvantages could be overcome through the application of rapid nondestructive methods to these purposes. Nondestructive testing techniques are well known and widely used in manufacturing processes. Unfortunately, the testing equipment that has been successful elsewhere has not performed well when applied to concrete. However, several researches, including NCHRP Project 10-6 (covered in *NCHRP Report 52,* 1968) and other studies conducted mostly by FHWA and by state highway departments in cooperation with FHWA, have produced information encouraging to the eventual application of nondestructive testing techniques to concrete. The present study adds further encouragement, and comes close to placing the state of the art within the realm of practicality.

The Pennsylvania Department of Transportation researchers, who conducted the study reported herein with support of researchers of The Pennsylvania State University, located and gave serious consideration to nine existing nondestructive testing instruments that appeared to have some potential for measuring pavement thickness. Two of these, and an additional device, were examined for determining reinforcement location and depth. Final selection of the most promising measurement techniques was made after applications on eight paving projects in six states. The techniques were used in conjunction with statistical acceptance criteria developed in the course of the project.

An ultrasonic gauge developed by the Ohio State University was found to perform thickness measurements for both plain and reinforced pavement with acceptable accuracy. However, before it can be applied routinely, further development, for which success seems predictable, is needed to reduce its cumbrousness and improve its resistance to construction job-site rigors. An eddy current proximity gauge proved to be satisfactory for measuring the thickness of hardened plain (non-reinforced) concrete pavement, and seems also to be capable of determining the position of the reinforcement in reinforced concrete pavements. It cannot be used to determine the thickness of pavements containing steel reinforcement. A device called a "pachometer" was found to be satisfactory for use in determining the depth and position of distributed steel reinforcement in both plastic and hardened pavement concrete.

The current project appears to have made a definite contribution toward attaining the goal of a workable nondestructive technique for the inspection and control of portland cement concrete pavement thickness and reinforcement position, and certain of the findings may be applied by construction agencies either immediately or after a moderate amount of further field trial; however, important advances in equipment development and its application in these uses remain to be made.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-8 by the Pennsylvania Department of Transportation, with William G. Weber, Jr., P. E., Research Coordinator, and Richard L. Grey, P. E., Materials Engineer, serving as Co-Principal Investigators. A portion of the work was subcontracted to The Pennsylvania State University, under the direction of Philip D. Cady, Associate Professor of Civil Engineering. The assistance of the following persons from the Pennsylvania Department of Transportation is acknowledged with appreciation: T. M. Shrawder, J. Miller, R. Neidich, and G. Bell, who assisted in compiling and obtaining data and offered constructive critiques of the methods and tests employed from a project engineering standpoint. Also acknowledged with appreciation is the assistance received from the following agencies and their representatives: the Federal Highway Administration and R. W. Moore, who aided in the resistivity and earth potential test methods; the Ohio Department of Highways and C. R. Hanes, and the Ohio State University and H. Mailer, who cooperated in the evaluation of the ultrasonic method; the Maryland State Roads Commission and N. L. Smith, Jr., who supplied data obtained with the pulse-echo ultrasonic gauge; The Pennsylvania State University and M. Huntzinger and W. Staude, who assisted in obtaining data, and L. Shuler, who helped to analyze the data.

The cooperation of the following states and their representatives in performing the Phase III field evaluations is gratefully acknowledged:

Louisiana—Verdi Adam, Materials and Research Engineer.
Maryland—Nathan L. Smith, Jr., Assistant Chief Engineer, Materials and Research.
Ohio—Leon Talbert, Research and Development Engineer.
Minnesota—Christian K. Preus, Research Coordination Engineer.
Utah—Dale E. Peterson, Engineer for Research.

RAPID MEASUREMENT OF CONCRETE PAVEMENT THICKNESS AND REINFORCEMENT LOCATION

FIELD EVALUATION OF NONDESTRUCTIVE SYSTEMS

SUMMARY

This research project was initiated to develop alternatives to the current method of determining pavement thickness and reinforcement location by coring. Coring is time-consuming, costly, destructive, and of no use in quality control during construction. Furthermore, existing acceptance criteria, dictated by the limitations inherent in coring, are widely diverse and generally lack a precise statistical basis.

The major findings of this research are that:

1. An appropriate nondestructive method exists for determining the thickness of concrete pavement after the concrete has gained its initial set.

2. Another nondestructive method is available for determining the thickness of nonreinforced concrete pavement in either the plastic or the hardened state.

3. A stable, accurate, and dependable device exists for determining the location and depth of reinforcement steel in pavements.

4. The application of statistical quality control techniques has led to the development of an acceptance specification for pavement thickness that is equitable to both the producer and the owner. Additionally, this specification reduces the risk to the owner of accepting pavements grossly deficient in thickness without an excessive increase in sampling costs.

5. Three alternate methods of application of penalties were studied. It is believed that the choice of method utilized is a prerogative of the individual specifying agencies.

6. A simple attribute sampling plan for location of reinforcement position was also developed in this research.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

That the load-carrying capacity of the pavement depends on its thickness is obvious. Quantitative data documented in the AASHO Road Test reports showed that, within the common range of rigid pavement thicknesses, an additional inch of thickness could have the potential for doubling the number of traffic loadings, in terms of 18,000-lb single-axle equivalent loads, over the life of the pavement. Also, where steel reinforcement has been used in highway pavements and structures, experience has shown that inadequately covered steel is frequently subject to the corrosive effects of deicing salts and moisture, resulting in spalling and potholes in the concrete. Thus, the importance of assuring compliance with specifications regarding both pavement thickness and location of reinforcement is readily evident.

All current methods for determining compliance with specifications regarding pavement thickness and reinforcement location begin with extracting core samples from the hardened pavement and measuring directly the thickness and reinforcement cover. Coring presents distinct problems aside from the fact that the cores are frequently taken long after the pavement has hardened and, although of value for record purposes, are of little use for quality control during the construction process. High cost, excessive handling and measuring time, and interference with continuity in the pavement are some of the problems. Also, the wide diversity in the techniques prescribed by highway agencies for obtaining and evaluating core data is clearly indicative of the general lack of sound sampling rationale, especially when applied to high-volume slip-form paving techniques.

The requirement of accurate determination of pavement thickness and reinforcement location and the shortcomings of the present systems lead quite logically to the identification of two areas of needed improvement. First, coring should be supplanted with more-rapid, less-costly, nondestructive techniques capable of measuring the pavement soon after placement to permit field adjustments to be made. Second, sampling techniques should be designed to balance quality assurance against cost while maintaining equitable consumer and producer risks. Where penalties are applied, they should be appropriate to the expected reduced pavement life. The development in recent years of several nondestructive test methods with the potential to determine pavement thickness and reinforcement location could lead to a solution of the first concern. If the capacity of nondestructive devices can be suitably demonstrated, the inherent speed of the nondestructive methods, compared with coring, will permit considerably greater flexibility in sampling programs leading to a solution of the second concern.

OBJECTIVES

The principal objective of the research described in this report was to evaluate currently available nondestructive testing systems for determining concrete pavement thickness and location of reinforcing steel in-situ either before or after the concrete has hardened. The development of improved procedures, including a guide specification for use on construction control and in determining pavement acceptability, constituted a corollary objective.

RESEARCH APPROACH

Pursuit of the objectives was carried out in three phases. The first phase consisted of a thorough review of the literature of nondestructive concrete testing and consultations with manufacturers of nondestructive test equipment to identify promising techniques for determination of pavement thickness and reinforcement position. The selected instruments were tested and compared with coring and surveyed thickness on eight 10 × 10-ft slabs cast on an outdoor test site. Variables in the test slabs included texture of the top surface; strength of concrete; slab thickness; presence, position, size, and type of reinforcement; smoothness of subbase; membrane between subbase and slab; and type of subbase material.

Phase II consisted of testing, on two highway construction projects in Pennsylvania, those test methods that showed promise in the Phase I slab studies.

Phase III consisted of testing, on eight highway construction projects in six states, those test methods that showed promise and proved to be practical in the field in the Phase II studies. Also, acceptance testing specifications for pavement thickness and reinforcement location, developed during Phase II, were field tested and compared against existing state specifications. Alternative methods of applying penalties were also studied.

CHAPTER TWO

RESEARCH FINDINGS

LITERATURE SEARCH

The literature was reviewed to locate all available equipment or methods for determining pavement thickness and reinforcement location (see Appendix A). Manufacturers who produced or were developing such equipment were located. All equipment available at the initiation of Phase I was included in the Phase I evaluation program. Two more devices became available in time for inclusion in the Phase II testing. Instrument selection and preliminary evaluation are given in Appendix B.

The literature study also identified the major factors that influence concrete thickness and reinforcement location determinations. For concrete thickness, influencing factors are surface condition, strength, thickness, bottom condition, base material, and the presence or absence of reinforcement. For reinforcement location determination, these include reinforcement depth, type, spacing, bar sizes, and number of layers. Minor factors not considered in the thickness program include type of cement, type of aggregate, and thickness of base; for reinforcement location, factors not studied included type of steel, combinations of reinforcement, and edge-of-pavement effect.

THICKNESS AND REINFORCEMENT LOCATION MEASUREMENTS ON TEST SLABS

General

In order to conduct a systematic testing program involving several instruments and the major influencing factors mentioned, special test slabs were constructed. Details of the slab construction and of the evaluation of the test instruments on the slabs are presented in Appendix C.

Instrument Evaluations

Five instruments were evaluated on the test slabs for pavement thickness measurement. Additionally two of these were evaluated with regard to determining reinforcement location, and one method for locating reinforcement only was also evaluated. Several of the instruments were tested in the laboratory to determine how they are affected by the extremes of temperature and relative humidity likely to be found in the field.

Of the two ultrasonic devices of thickness measurement tested on the small slabs, the one operating under the resonant frequency principle presented the greater operational difficulty. For proper performance a nearly perfect sine wave voltage source was required. Also, high pavement temperatures had a considerable adverse effect on gage operation. In addition, it was difficult to decide how to interpret the oscilloscope readout. The other ultrasonic device, which operates on the rebound signal principle, was developed by personnel from The Ohio State University (OSU), under a research agreement with the Ohio Department of Highways in cooperation with the Federal Highway Administration; and, during this phase of the testing, it was operated by OSU representatives. In general, the OSU device operated quite well during this testing phase. Both of these devices require use of a viscous liquid couplant to preclude the existence of air voids between the transducers and the pavement. The amount of couplant required by the OSU gage was considerably larger—approximately one pint per test—than that used by the other ultrasonic gage. The original configuration of the OSU gage consisted of separate laboratory electronic components, which were not well suited to field use.

A nuclear device for measurement of pavement thickness, as proposed in an earlier NCHRP report (*62*), proved to offer a considerable number of unexpected difficulties. Much time was lost in locating the points on the pavement surface directly above the implanted radioactive sources. In the initial slab tests, radiation rates appeared to vary in an illogical manner. Subsequent special tests pinpointed the problems as stemming largely from inherent deficiencies in the detection equipment (e.g., autocollimation). Because the available equipment was not suitable for slab thickness determination, the nuclear method was eliminated from further consideration. It should be pointed out, however, that the principle involved in the nuclear method remains valid, and the development of nuclear detection equipment designed for pavement thickness measurement is deserving of further attention, although beyond the scope of this study.

The resistivity gage was the only device that, at the time of its selection, was conceived to have the dual capability of pavement thickness and reinforcement depth determination. This test method requires that the pavement surface at the point of contact with the probes be wetted by an electrolyte. The interpretation of data obtained by this method is a major difficulty. Material changes that would indicate pavement thickness and reinforcement depth are detected only by slope changes in the data plots. The use of a computer program for interpretation of data gathered during the Phase II field testing under this project was very advantageous in that data interpretation was standardized, but the device appeared still to lack the necessary sensitivity to accurately determine thickness.

The eddy current proximity gage, a NASA development obtained originally for measuring pavement thickness, was found during the slab studies to be capable also of detecting the presence of reinforcement. This instrument uses low-power radio frequency radiation to induce eddy currents in aluminum foil, plate, or screen placed at the bottom of the slab before paving, or in mesh-type reinforcement. Power loss to a receiving antenna due to the eddy current production is proportional to the distance from the antenna to the mesh reinforcement or aluminum foil. Although this equipment generally operated quite well, readings drifted and were erratic at high ambient temperatures. This problem was later corrected by changes in circuitry. The instrument displayed the smallest standard deviation in pavement thickness determinations of all of the instruments studied. A calibration curve is required for the device, and the relatively flat slope for depths greater than 8 in. originally presented accuracy problems. A later modified device was shown capable of detecting depths to approximately 15 in.

The pachometer, which detects the depth and spacing of reinforcing steel by completion of a magnetic circuit, has been in use with reported success for some time. The instrument is small, simple, and virtually trouble-free. A separate calibration should be carried out for each type and size of reinforcement to be used. The ability of this instrument to accurately measure reinforcement depth is limited to about 5 in., where flattening of the calibration curve begins to reduce accuracy noticeably.

Effect of Slab Variables

Various statistical studies were made of the data obtained with the several instruments on the test slabs for the purpose of determining accuracy of the instrument readings and the effects of the slab variables on instrument operation and reliability.

The nuclear method, in addition to the instrumentation problems cited earlier, was found to be overly sensitive to variations in the condition of the slab bottom, presence of asphalt membrane, and subbase type.

Concrete strength, bottom condition, and base type were ascertained to make a contribution to variance in the resistivity method that was significant at the 95-percent confidence level. The resistivity method is as suitable for use on fresh concrete as on hardened concrete, and statistically it is favored over the nuclear method. Only the resistivity method is capable of indicating multiple layers of bar or mesh reinforcement. The device showed favorable statistical analysis data in its application of reinforcement depth determinations on the test slabs.

Data were insufficient to perform an analysis of variance for the purpose of examining contributions of the various slab design factors to over-all variance of the OSU ultrasonic gage readings. The four factors found to have a significant effect on the measurements of the resonant frequency ultrasonic gage—strength of the concrete, slab thickness, bottom condition, and base type—should apply to the OSU ultrasonic gage as well. Data seem to indicate that neither of these ultrasonic gages produces reliable results on concrete that has not reached an initial set. Although the OSU gage produced measurements significantly different from those determined by differential levels, the standard deviation and mean deviation—at 0.768 and 0.12 in., respectively—were not excessively large. This indicated that with a correction factor the method might have good potential for use in pavement thickness determinations. The resonant frequency ultrasonic gage was highly erratic as indicated by a mean standard deviation and mean deviation from differential levels of 1.800 and 2.43 in., respectively.

The eddy current proximity gage had a lower mean standard deviation (0.248 in.) than any of the other instruments used for pavement thickness testing. It was discovered by accident that this gage is quite capable of accurately measuring the depth of mesh reinforcement when a correction factor is applied.

The factors having a significant effect on pachometer determinations of reinforcement depth are surface condition, bar size, bar depth, bar spacing, number of layers of bars, and interaction between bar size and surface condition. The mean standard deviation for the pachometer was only 0.159 in. The pachometer is suitable for use on concrete very soon after placement and is excellent for determining the spacing of reinforcing bars. This instrument holds as much promise for accurate determination of mesh depth as for bar depth provided that a reliable calibration is performed.

FIELD TESTING CONSTRUCTION JOBS

General

As a result of the initial evaluations on the eight outdoor test slabs, the following instruments were accepted for field evaluation on two construction jobs in Pennsylvania in the summer of 1971:

1. For slab thickness:
   (a) OSU ultrasonic gage.
   (b) Resistivity gage.
   (c) Eddy current proximity gage.
2. For reinforcement depth:
   (a) Pachometer.
   (b) Resistivity gage.
   (c) Eddy current proximity gage (mesh reinforcement only).

Two new methods also investigated during this phase were (1) the earth electrical potential method developed by the Federal Highway Administration and (2) the pulse-echo ultrasonic method developed by the Maryland State Roads Commission.

Two construction projects in south-central Pennsylvania were chosen for the field testing under Phase II of this research project. These projects included the factors of (d) design thicknesses of 9 and 10 in., (b) bar and mesh reinforcement, and (c) subbases of coarse gravel and limestone. Slip-form pavers were used on both projects. The paving on one project was done in two lifts to facilitate placement of the steel fabric reinforcement. Five test areas, each consisting of 1,000 ft of pavement two lanes in width, were selected on each job. In general, 20 readings were obtained with each instrument in each test area, yielding approximately 100 readings per instrument for each job.

Instrument Performance

At the start of the program an attempt was made to operate from a bridge across the pavement directly behind the paving train, but this proved impracticable.

PennDOT personnel operated the OSU gage during this phase and experienced only minor difficulties. Statistical analysis indicated that the OSU gage produced excellent results, but it is evident that a standardization procedure will have to be used for each job. It is logical to conclude that certain changes in influencing factors on an individual job would require a restandardization so that the same peaks are used for the delay time and transient time in order that they be comparable.

Performance of the pachometer was very satisfactory, but the resistivity gage was a disappointment on both projects. Each test required 15 to 20 min. Efforts were made to improve the operational efficiency of the resistivity method. A computer program was very successful in reducing raw data to thickness values, and the resistivity meter was replaced with a more sensitive model that yielded improved field readings. However, these improvements failed to overcome the basic difficulties, which are discussed in Appendix D.

Although the presence of mesh reinforcement in the pavement was known to preclude the use of the eddy current proximity gage for pavement thickness determinations, the adverse effect of longitudinal and transverse reinforcing bars when clipped together was unexpected. However, this device was sufficiently sensitive in the detection of wire-mesh reinforcement to warrant the construction of a calibration curve.

Other Methods Evaluated in Phase II

Two new methods were brought to the attention of the researchers during Phase II of this project. The natural earth, electrical potential method was demonstrated by its inventor, R. W. Moore of FHWA, on one of the paving jobs selected for field testing. It was found unsuitable for field use in its present stage of development. The pulse-echo ultrasonic method developed by the Maryland State Roads Commission was not actually employed by the researchers under this research project. Based on information gained by the principal investigators during two visits to Maryland, it was adjudged that the device did not appear to possess sufficient sensitivity to warrant its inclusion in the field testing under Phase III of this project. The researchers were of the opinion that thought should be given to calculations based on an actual measurement of the velocity of the ultrasonic pulse in the concrete being tested rather than the empirical calibration technique presently being used.

ACCEPTANCE SPECIFICATIONS

A study of the acceptance specifications for pavement thickness and the penalties for deficient thickness used by several states (Appendix E) revealed a diversity of control sampling and enforcement procedures. The most frequent sampling procedure allows one core to represent 1,000 ft of one lane. In most cases full payment is allowed to the contractor for deficiencies up to 0.25 in., with complete removal for deficiencies greater than 0.5 in. Both the sampling procedures and acceptance criteria were developed many years ago prior to high-speed, slip-form paving methods, and they are somewhat inefficient and arbitrary in light of today's needs.

Evaluation of pavement thickness measurement by coring, as a result of this research and from data taken from the literature, has shown that the mean standard deviation for pavement thickness is approximately 0.3 in. Using appropriate statistical procedures (illustrated in Appendix E), it can be shown that at least four samples (rather than the usual one) are needed to assure that the true average pavement thickness is no less than 0.25 in. smaller than the specified value if the sample average is equal to the specified thickness. This type of approach to rational acceptance sampling is known as "sampling by variables." It is a reliable and easily understood approach, but it does not lend itself to easy application in the field. It is cited here to illustrate the inadequacies of the present sampling procedures, and it was used in the research to determine necessary sample sizes for required confidence levels as well as to rank instruments in accordance with their demonstrated variance. A better technique for field application is the one known as "sampling by attributes." This technique was used to devise two alternative sampling specifications for trial use in the Phase III field studies. Actually three alternative specifications were examined because one of the two formerly mentioned plans was evaluated at two different sampling levels. The details of the proposed alternative acceptance procedures are given in Appendix E. Operating characteristics curves for the three alternative specifications were determined by means of computer simulation. Alternative specification I, which featured (a) a sample size of six, (b) a penalty limit of one for a sample mean equal to or greater than the specified thickness, and (c) a rejection limit of one for deficiencies greater than ½ in. with a sample mean less than the specified thickness, proved to be better than the other two. Of the three plans tested, it provided the most equitable balance of producer and consumer risks having a producer's risk of 12 percent at the 10-percent-defective level and a consumer's risk of 12 percent at the 50-percent-defective level. All three plans were also evaluated in the Phase III field study.

Review of the practices among the states for applying penalties for reduced pavement thickness indicated that this was apparently an arbitrary procedure. It would appear that penalties should be a function of either reduced yardage of pavement placed or the anticipated reduction on pavement life. The following three methods utilized in Phase III applied penalties based on:

1. Reduction of yardage placed (percentage of design thickness).
2. Area deficient in thickness (number of tests per lot deficient).
3. Reduction in expected number of load applications (average thickness of the lot).

MULTISTATE FIELD STUDY

General

Based on the experience obtained with the various instruments in the Phase II field studies, the OSU ultrasonic gage and the eddy current proximity gage for determining pavement thickness, and the pachometer for determining reinforcement position, were selected for further field studies. These instruments were evaluated in conjunction with the proposed acceptance specifications on eight paving jobs in six states during the 1972 construction season. Details of this study are presented in Appendix F.

Instrument Performance

The eddy current proximity gage performed satisfactorily in measuring thickness of nonreinforced pavement. The newer version of this instrument used in this phase proved to be stable and performed without any breakdowns in the field. The OSU gage, which was a combination of laboratory-type components, suffered a number of breakdowns in the field. However, when operating properly, this instrument, as in previous studies, gave good results. It is believed that the field service factor for this equipment could be considerably improved with the development of electronic circuitry designed to withstand the rigors of field work. Occasionally, difficulty was experienced in obtaining a good coupling between the transducers and the pavement surface. It was also found that poorly defined signals often occur on pavements constructed on asphalt-treated subbases resulting in scans that are difficult to interpret and that necessitate the use of empirical conversion factors. Nevertheless, the generally good performance and accuracy of the readings, coupled with speed of operation and suitability for both reinforced and nonreinforced pavements, result in high recommendation for the OSU ultrasonic gage.

The pachometer operated with high reliability and performed excellently within its capabilities. On one job where the design depth of the reinforcement was 5 in. minimum, the pachometer readings were virtually worthless since the maximum range of the instrument is 4 to 5 in. This may not be a serious deterrent to the use of the pachometer for pavement acceptance. When the reinforcement is deeper than the effective range of the instrument, the depth is probably greater than the specified value, which is usually a minimum figure. Also, there is probably more than sufficient cover over the reinforcement to prevent corrosion and spalling.

Application of Acceptance Specifications

In the field, as in the previous computer simulation study, the alternative acceptance specification involving a single-attribute sampling plan consisting of six specimens per sample appeared to give the best results for pavement thickness. While it proved to be somewhat more severe than the acceptance specification currently employed in the states in which the tests were carried out, its severity serves to illustrate the lack of protection afforded by the present specifications. For example, using the core data, in instances where the existing state specifications would have accepted without penalty 100 percent of the areas tested, the most equitable of the proposed alternative acceptance specifications would have also accepted all of the pavement sections, but would have imposed penalties on 8 percent of them.

The use of the nondestructive means of pavement thickness determination in conjunction with the proposed acceptance specifications produced somewhat higher percentages of penalty and rejection situations than did the core measurements. Because the over-all variances were not significantly different, it was concluded that greater attention to calibration or standardization of the nondestructive instruments would probably make the results more comparable.

The small number of lots to which penalties would be applied made comparison of the three penalty methods difficult. The severity of any one penalty method depended greatly upon the individual test results in a lot. It appears that the use of any penalty method should be the prerogative of the individual states. However, the researchers feel that there should be a rational basis for the penalty, such as reduced yardage or reduced life expectancy.

The proposed acceptance specification for location of reinforcement consisted of acceptance if the average of two determinations per 100 ft by one lane of pavement equaled or exceeded the specified depth minus ½ in. No difficulty whatsoever was experienced in meeting this specification on two of the three jobs where pachometer tests were carried out. On the third job, occasional failures to meet this specification were encountered. However, the specified depth in this case was so deep that, even in the cases where the proposed specifications were not met, little danger of corrosion or spalling exists.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

INSTRUMENTATION

Pavement Thickness Measurement

The OSU gage, an ultrasonic gage which operates on the rebound principle, proved to be the most suitable nondestructive device for measurement of pavement thickness. It can be used on either reinforced or nonreinforced pavements. When properly standardized, it can produce results approaching in accuracy those from core measurements. The device can be used on pavement as soon as the concrete has attained its initial set, and measurements can be obtained rapidly with this instrument. The present instrument, however, exists only in prototype form, an aggregation of laboratory-type electronics, and has been susceptible to breakdown under the extremes of temperature, humidity, and handling encountered in the field. It is believed that this drawback can be overcome by development of equipment especially designed for field conditions. Also, occasional difficulty may be encountered in obtaining suitable signals. This may be due to lack of proper coupling of the transducers to the pavement surface or to certain subbase conditions. Nevertheless, the generally excellent results with this equipment along with its ease of use and nondestructive character should enable it to augment or even largely replace coring for determination of pavement thickness.

For nonreinforced pavements, the eddy current proximity gage possesses certain advantages over the OSU gage. The data can be obtained more rapidly and the instrument is lighter in weight and can be used on plastic concrete. It achieves comparable accuracy. Although a prototype, it has proven to be stable and rugged under field conditions. It does possess the disadvantage, however, of requiring placement of metal foil or screen on the subbase at points of measurement before the pavement is placed. Also, it is not suitable for use on reinforced concrete pavements.

It should be stressed that both of these instruments require occasional standardization checks for accuracy assurance.

The resistivity method of determining pavement thickness reported herein was found to be inaccurate and time-consuming. These conclusions are opposite of those set forth in an FHWA report.* The reasons for these differences are not readily apparent, and the search for an explanation was beyond the scope of this project.

Reinforcement Position Determination

The magnetic induction type of instrument, characterized by the pachometer used in this research, was found to be the only type capable of nondestructively determining reinforcement position in concrete pavement. It can be used on plastic or hardened concrete. It is accurate, reliable, and able to withstand the rigors of field use. However, like all of the nondestructive electronic devices, it should be carefully calibrated for each type of application and its calibration should be occasionally checked.

ACCEPTANCE SPECIFICATIONS

Pavement Thickness Measurement

A review of current acceptance specifications for pavement thickness revealed them to be widely diverse and, in general, lacking a precise statistical basis. Furthermore, most of them afford little protection against obtaining pavements that are deficient in thickness. Published information, based on data from the AASHO Road Test, has shown the importance in terms of long-term load-carrying capacity of as little as 1 in. of pavement thickness. It is recognized that the time, cost, and destructiveness of coring operations have discouraged the use of more reasonable standards of quality evaluation in regard to pavement thickness. The capabilities of the more-rapid nondestructive devices, proven in this research, should provide the impetus for a more rational approach to acceptance testing.

Three acceptance specifications were examined in this research. Evaluations were made in terms of providing equitable levels of risk to the producer and to the consumer, while at the same time attempting to minimize the amount of acceptance testing required. Of three plans examined, a single-attribute sampling program requiring only six specimens per sample was found to be superior. It is strongly urged that highway agencies seriously consider adopting this or a similar attribute sampling scheme in their respective states.

Three methods of applying penalties, in conjunction with the improved sampling procedures, were suggested in this research. Data from the Phase III field studies of this research are not sufficient to warrant an appraisal of the penalty systems proposed. Furthermore, it is believed that the choice of penalty system is largely a matter of being dictated by the policies of the respective states.

Reinforcement Position Location

The depth of cover of reinforcement in pavement does not possess the critical aspects that it does in bridge decks and other highway structures. However, assurance must be sought that sufficient minimum cover is maintained to prevent corrosion of the reinforcement and resultant spalling. The speed and accuracy of the pachometer in conjunction with a single-attribute sampling plan devised in this research are capable of providing this assurance.

* "Electrical Resistivity Instruments for Measuring Thickness and Other Characteristics of Pavement Layers." *Rept. No. FHWA-RD-73-2* (Aug. 1972).

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The conclusions listed in the following subsections appear to be warranted on the basis of the research conducted on this project.

Instrumentation

1. Of the ultrasonic methods for measurement of pavement thickness, only the OSU gage appears to present sufficient all-around capability at this time to warrant use.
2. The OSU gage will have to be redesigned to better withstand the rigors of field use before it can be wholly considered as a practical field tool.
3. The OSU gage cannot be used on plastic concrete.
4. The eddy current proximity gage is suitable for determination of the thickness of nonreinforced pavements. It can acquire data more rapidly than the OSU gage, is easy to handle and stable, and can be used on plastic or hardened concrete. Additionally, it can be used to locate the position of wire-mesh reinforcement in pavement.
5. The pachometer is a highly stable and accurate device for determination of reinforcement location. It is suitable for use on both plastic and hardened concrete for reinforcement depths of less than 5 in.
6. All of the nondestructive electronic gages should be standardized for each type of pavement, reinforcement, and subbase condition; and the standardization should be checked occasionally.
7. Present resistivity methods of determining pavement thickness and position of reinforcement are time-consuming and inaccurate because of difficulty in interpreting the appropriate inflection points in the data.
8. The pulse-echo ultrasonic method of determining pavement thickness appears to have potential, but it requires refinement before it can be thoroughly evaluated for possible use.
9. The nuclear method, with the detection equipment used in this study, was not capable of accurately determining pavement thickness.
10. A mechanical impact-type device for measuring pavement thickness, evaluated in this research, failed to provide satisfactory results.
11. Determination of pavement thickness by probing concrete appears to possess too many sources of human bias associated with real measurement problems to justify its use as a quality control technique.

Acceptance Specifications

1. Current state acceptance criteria for pavement thickness are widely diverse and generally lack a precise statistical basis.
2. A single-attribute sampling acceptance procedure that provided an equitable balance between consumer and producer risks with minimal sampling was developed in this research for use in pavement thickness acceptance.
3. Present state penalty methods are somewhat arbitrary and, in general, lack a rational basis. The use by individual states of a rational method, such as used in this study, is urged. The individual method used should be the prerogative of each state.
4. Acceptance sampling with regard to reinforcement depth can be accomplished with minimal effort using the pachometer and the acceptance criteria developed in this research.

SUGGESTED RESEARCH

Based on the results of the research carried out on this project, the following areas require further research:

1. The OSU ultrasonic gage needs improvement in the degree of coupling between the transducers and the pavement, especially in view of the current trend toward coarser pavement surface textures. Also, more developmental work is needed toward providing more compact equipment that is less sensitive to environmental changes and the rigors of field use.
2. The pulse-echo technique for determination of pavement thickness should be developed further, especially with the thought of incorporating velocity measurements to improve the reliability of the readings.
3. The nuclear method should receive additional developmental work with regard to the detection device in order to eliminate the causes of the variability observed in this research. Possible unintended collimation effects within the detection device should be investigated.
4. If suitable microwave or radar gages for determining pavement thickness reach the prototype stage, they should be evaluated.
5. Additional research should be carried out on acceptance sampling to optimize costs due to risks to both the producer and the consumer and to sampling as well.
6. Additional research should be carried out on a rational method of applying penalties.

REFERENCES

1. Chree, C., "On Longitudinal Vibrations." *Quart. Math. J.*, Vol. 23 (1889) pp. 317-342.
2. Sutherland, W., "A Kinetic Theory of Solids with an Experimental Introduction." *Philos. Mag.* (London), Vol. 32, Ser. 5 (1891) pp. 31-43, 215-225, 524, 533.
3. Lord Rayleigh (John W. Strutt), *The Theory of Sound.* Vol. 1, Chap. 5, 7, 8. 2nd Ed. MacMillan, London (1894).
4. Pierce, G. W., "Magnetostriction Oscillators." *Proc., Am. Acad. Arts and Sci.*, Vol. 63 (1928) p. 1; *Proc., Inst. Radio Eng.*, Vol. 17, No. 1 (Jan. 1929) pp. 42-88; *Sci. Abst.*, Sec. A—Physics, Vol. 31, Abst. No. 2500 (1928).
5. Bernhard, R. K., and Spaeth, W., "Dynamic Method of Investigating Stresses in Buildings" (in German). *Der Stahlbau* (Berlin), Vol. 2, No. 6 (Mar. 22, 1929) pp. 61-68.
6. Coyne, A., "Acoustic Methods for Determining Stresses in Concrete Structures, Particularly Concrete Dams" (in French). *Acad. des Sci., Comptes Rendus*, Vol. 194 (1932) p. 592; *Genie Civil* (Paris), Vol. 100 (1932) p. 225; Vol. 113 (1938) pp. 286-288; Abst. in *Eng. Index 1932*, p. 291.
7. Grime, G., "The Determination of Young's Modulus for Building Materials by a Vibration Method." *Philos. Mag.* (London), Vol. 20, No. 132 (1935) pp. 304-310; *Bldg. Sci. Abst.*, Vol. 8, Abst. No. 1307 (1935).
8. Ide, J. M., "Comparison of Statically and Dynamically Determined Young's Modulus of Rocks." *Proc. Nat. Acad. Sci.*, Vol. 22, No. 2 (Feb. 1936) pp. 81-92; *Bldg. Sci. Abst.*, Vol. 9, Abst. No. 828 (1936).
9. Bernhard, R. K., "Highway Investigation by Means of Induced Vibrations." *Eng. Exp. Station Bull. 49*, Penn. State College (Oct. 2, 1939); Abst. in *Eng. Index 1940*, p. 1048.
10. Hornibrook, F. B., "Application of Sonic Methods to Freezing and Thawing Studies of Concrete." *ASTM Bull. No. 101*, pp. 5-8 (Dec. 1939).
11. Meyer, E., and Bock, E., "Sonic and Ultrasonic Testing of Concrete Beams with Cracks" (in German). *Akustiche Zeits.* (Leipzig), Vol. 4, No. 4 (1939) pp. 231-237; *Bldg. Sci. Abst.*, Vol. 13, Abst. No. 596 (1940).
12. Meyer, E., "Transmission of Supersonic Sound in Setting Cement." *Electroacoustics*, Oxford Press, Toronto (1939) pp. 23-25.
13. Thomson, W. T., "Measuring Changes in Physical Properties of Concrete by the Dynamic Method." *Proc. ASTM*, Vol. 40, pp. 1113-1129 (1940).
14. Long, B. G., Kurtz, H. J., and Sandenaw, T. A., "An Instrument and a Technique for Field Determination of the Modulus of Elasticity and Flexural Strength of Concrete Pavements." *J. ACI*, Vol. 16, No. 3 (Jan. 1945) pp. 217-231.
15. Bradfield, G., "New Electro-Acoustic Transducer Operating with Short Pulses." *Electronic Eng.*, Vol. 20, No. 241 (Mar. 1948) pp. 74-78.
16. Jones, R., "The Application of Ultrasonics to the Testing of Concrete." *Research* (London) (May 1948) p. 383.
17. Cheesman, W. J., "Dynamic Testing of Concrete with the Soniscope Apparatus." *Proc. HRB*, Vol. 29 (1949) pp. 176-183.
18. Jones, R., "Measurement of Thickness of Concrete Pavements by Dynamic Methods: Survey of Difficulties." *Mag. of Concrete Res.* (London), No. 1 (Jan. 1949) pp. 31-34; Abst. in *Eng. Index 1949*, p. 1021.
19. Van Valkenburg, H. E., "The Theory of Ultrasonic Materials Testing." *Mech. Eng.*. Vol. 71 (Oct. 1949) p. 817.
20. Leslie, J. R., and Cheesman, W. J., "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures." *Proc. ACI*, Vol. 46 (1950) pp. 17-30; disc., pp. 36-1, 36-2, 36-4.
21. Leslie, J. R., "Pulse Techniques Applied to Dynamic Testing." *Proc. ASTM*, Vol. 50 (1950) pp. 1314-1326.
22. Leslie, J. R., and Cheesman, W. J., "Soniscope for Examining Concrete Structures: Ultrasonic Method Detects Cracks and Deterioration." *Hydro Res. News* (Ontario), Vol. 2, No. 1 (Jan.-Mar. 1950) pp. 1-4.
23. Mason, W. P., *Piezo-Electric Crystals and Their Applications to Ultrasonics.* Chap. 15, pp. 29-32, 83, 90, 151. Van Nostrand, New York (1950).
24. Whitehurst, E. A., "Soniscope Tests Concrete Structures." *J. ACI* (1951) pp. 433-444.
25. Whitehurst, E. A., "The Soniscope—A Device for Field Testing of Concrete." *Proc., 37th Ann. Road School*, Eng. Ext. Dept., Series No. 77, Purdue Univ. Lafayette, Ind. (1951) pp. 105-111.
26. Whitehurst, E. A., "Use of the Soniscope for Measuring Setting Time of Concrete." *Proc. ASTM*, Vol. 51 (1951) p. 1166.
27. Jones, R., "Non-Destructive Testing of Concrete." *Reinf. Conc. Rev.* (London), Vol. 2, No. 5 (Jan. 1951) pp. 315-328.
28. Blanc, A., "Investigation of Different Categories of Transverse Waves Capable of Propagating Within Slabs." *Rilem Bull. No. 15* (Paris), Special Issue, "Vibration Testing of Concrete," First Part (Aug. 1953) pp. 23-37.
29. Dawance, G., and Blanc, A., "Measuring Apparatus, Measuring Technique, Diverse Cases of Propagation." *Rilem Bull. No. 15* (Paris), Special Issue, "Vibrating Testing of Concrete," First Part (Aug. 1953) pp. 1-23.

30. DAWANCE, G., "Recommendations for Determining the Quality of Concrete by Measuring the Speed of Sound." *Rilem Bull. No. 13* (Paris) (Mar. 1953) pp. 75-77.
31. LALSNE, F., and CLOQUET, J. L., "Testing of Concrete by an Electromagnetic Method-1" (L' Essai non destructif des ouvrages en beton arme). *La Tech. Modern—Construction* (Paris), Vol. 9, No. 4 (Apr. 1954) pp. 119-124.
32. DEPELSENAIRE, H., "Dynamic Vibrations of Concrete—Application of Acoustical Methods of Determining Some Mechanical Characteristics" (in French). *Travaux* (Paris), Vol. 38, No. 240 (Oct. 1954) pp. 753-762.
33. EISENMANN, J., and STEINKAMP, G., "Measurement of Depths and Widths of Concrete Cracks by Ultrasonic Test Methods" (Messung der Tiefen and Weiten von Betonrissen mitteld Ultraschall). *Beton-u Stahlbetonbau* (Berlin), Vol. 49, No. 2 (Feb. 1954) pp. 36-38; Abst. in *Eng. Index 1954,* p. 228.
34. KESLER, CLYDE E., and HIGUCHI, YOSHIRO, "Problems in the Sonic Testing of Plain Concrete." *Rilem, Internat. Symp. Nondestructive Testing of Materials and Structures* (Paris), Vol. 1, Paper No. A-4 (Jan. 1954) pp. 45-53. *Rilem Bul. No. 17,* Second Part, Summ. No. 3 (Apr. 1954).
35. CHANG, TIEN-SUN, "Prediction of the Rheological Behavior of Concrete from its Sonic Properties." Doctoral dissertation, Univ. of Illinois, Urbana (1955); Abst. in *Dissertation Absts.,* Vol. 16, No. 2 (Feb. 1956) p. 308.
36. JONES, R., "Vibration Method for Measuring Thickness of Concrete Road Slabs in Situ." *Mag. of Concrete Res.* (London), Vol. 7, No. 20 (July 1955) pp. 97-105; *Hwy. Res. Abst.,* Vol. 26, No. 2 (Feb. 1956) p. 8.
37. TRUELL, R., "Ultrasonic Attenuation Measurements for Study of the Engineering Properties of Materials." Paper 55-S-17, ASME Annual Meeting, Chicago, Nov. 13-18, 1955; Abst. in *Appl. Mech. Rev.,* Vol. 9, Abst. No. 1295 (Apr. 1956).
38. WESCHE, J., "Determination of Damages in Reinforced Concrete Constructions with Ultrasonics." *Rilem, Symp. on the Observation of Structures* (Lisbon), Vol. 2 (1955) pp. 153-158.
39. ELVERY, R. H., and VALE, D. W., "Portable Ultrasonic Concrete Testing Apparatus." *Mag. of Concrete Res.* (London), Vol. 7, No. 21 (Nov. 1955) pp. 161-164.
40. CHANG, T. S., and KESLER, C. E., "Correlation of Sonic Properties of Concrete with Creep and Relaxation." *Proc. ASTM,* Vol. 56 (1956) pp. 1257-1272.
41. CHANG, T. S., and KESLER, C. E., "Prediction of Creep Behavior in Concrete from Sonic Properties." *Proc. HRB,* Vol. 35 (1956) pp. 436-443.
42. LAMB, D. R., "A New Soniscope—'The Elastiscope.' " *Proc. HRB,* Vol. 35 (1956) pp. 418-423.
43. JONES, R., ET AL., "Discussion on the Ultrasonic Testing of Concrete." *Struct. Eng.* (London), Vol. 35, No. 5 (May 1957) pp. 190-206.
44. SPENCER, R. W., and LAVERTY, B. R., "Appraising the Quality and Performance of Concrete by Pulse Velocity Measurements—Symposium 1958." *HRB Bull. 206* (1959) pp. 46-56.
45. MEYER, R. C., "Eight Years of Pulse Velocity Tests on Concrete Pavements in Kansas." *HRB Bull. 206* (1959) pp. 31-36.
46. AKASHI, TOYOKI, "On the Attenuation Constant of Ultrasonic Wave in Concrete by Immersion Method and Multiple Echo Method" (in Japanese with English summary). *Semento Gijutsu Nenpo* (Tokyo), Vol. 13 (1959) pp. 375-380.
47. CHATTERJEE, P. N., and SEN, B., "Use of Resonant Frequency Method as Standard for Non-Destructive Testing of Concrete." *J., Inst. Eng.* (Calcutta), Vol. 39, No. 10, Part 1 (June 1959); pp. 985-998 Abst. in *Eng. Index 1959,* p. 268.
48. EISENMANN, K., and ODEWALD, G., "Properties of Concrete: Analysis of the Elastic Properties of Concrete by Means of Ultrasonic Waves" (Untersuchung der elastischen Eigenschaften von Beton mittels Ultraschall). *Beton- u Stahlbetonbau* (Berlin), Vol. 54, No. 6 (June 1959) pp. 156-158.
49. POCHTOVIK, G. Y., "Ultrasonic Testing of a Bridge Pier" (in Russian). *Avtom. Dorogi* (Moscow) Vol. 24, No. 8 (1961) pp. 22-23; *Road Absts.,* Vol. 28, Abst. No. 1169 (Nov. 1961).
50. GROSMANGIN, M., KOKESH, F. P., and MAJANI, P., "A Sonic Method for Analyzing the Quality of Cementation of Borehole Casings." *J. Petrol. Tech.,* Vol. 13, No. 2 (Feb. 1961) pp. 165-171.
51. FACAOARU, I., "Contribution to the Study of the Relationship Between the Compressive Strength of Concrete and the Longitudinal Ultrasonic Velocity" (in French with English summary). *Rilem Bull. No. 12* (Sept. 1961) pp. 125-154.
52. MUENOW, R., "A Sonic Method to Determine Pavement Thickness." *J. PCA Res. Devel. Lab.,* Vol. 5, No. 3 (Sept. 1963) pp. 8-21.
53. BRUNETTI, M., "Dynamic Auscultation of Concrete." *Bull. Liaison Labs.* (Routiers, France), No. 11 (Jan. 1965) pp. 5.1-5.12.
54. JONES, R., and MAYHEW, H. C., "Thickness and Quality of Cemented Surfacings and Bases Measuring by a Non-Destructive Surface Wave Method." *Civil Eng. Pub. Works Rev.* (UK), Vol. 60, No. 705 (Apr. 1965) pp. 523-529.
55. JONES, R., "Non-Destructive Road Tests Using Surface Waves." *Australia Civil Eng. Constr.,* Vol. 6, No. 1 (May 1965) pp. 46-51.
56. GOLIS, M. J., MCMASTER, R. C., TOTH, L., and COOPER, G., "The Development of Ultrasonic Non-Destructive Testing Instrumentation to Measure Pavement Thickness." *Report No. 208-3,* Eng. Exp. Stat., The Ohio State Univ., Columbus (Dec. 1966).

57. MOAVENZADEH, F., and MCMASTER, R. C., "Potential Uses of Sonic and Ultrasonic Devices in Highway Construction." *NCHRP Rep. 25* (1966) 48 pp.
58. "Sonic Testing of Materials." *Batir* (France), No. 146 (Mar. 1966) pp. 33-38.
59. CANFIELD, JR., and MOORE, W. H., "Development of Instrument for Non-Destructive Measurement of Concrete Pavement Thickness. *HPR- 1-9-63-61,* Texas Hwy. Dept. for U.S. Bur. of Public Roads.
60. "Proposed Tentative Method of Test for Pulse Velocity Through Concrete." ASTM C597 (1967) pp. 10-14.
61. NEPPER-CHRISTENSEN, P., "Measurement of Ultrasonic Pulse Velocity in Green Concrete." Concrete Res. Lab., Denmark (1968).
62. HAWKINS, S. D., "Measurement of Pavement Thickness by Rapid and Non-Destructive Methods." *NCHRP Rep. 52* (1968) 82 pp.
63. RIFFLE, H., "Ultrasonic Testing." U.S. Bur. of Reclamation (Sept. 1968).
64. RAJAGOPALAN, P. R., "Non-Destructive Testing of Concrete Using Pulse Velocity and Attenuation." *Cncl. Scient. & Indus. Res.,* Central Building Research Inst., India (Feb. 1968).
65. BELLIS, W. R., BORUP, R. E., and FIKE, I. F., "Non-Destructive Testing to Determine Thickness and Integrity of Concrete Slabs and Decks." New Jersey Dept. of Transportation (Nov. 1968).
66. GOLIS, J. J., "Pavement Thickness Measuring Using Ultrasonic Pulses." *HRB Record No. 218* (1968) pp. 40-48.
67. JONES, R., HARLAND, D. G., LISTER, N. W., and THROWER, E. N., "Non-Destructive Testing in Relation to Highways." Contract No. FH-11-6744, U.S. Bur. of Public Roads.
68. JAULLITE, W. M., "Locating Metal Embedded in Concrete." *J. ACI* (Feb. 1958) pp. 705-707.
69. HALSTEAD, P. E., "The 'Covermeter'—Apparatus for Measuring the Depth of Reinforcement Below the Surface of Hardened Concrete." *Tech. Rep. TRA/ 197* (Res. Note xRP-5), Cement and Concrete Assn., Great Britain (May 1951).
70. "New Instrument, Measure Concrete-Reinforcement Cover." *Commonwealth Eng.* (Melbourne), Vol. 39, No. 7 (Feb. 1, 1952) p. 287; *Hwy. Res. Abst.,* Vol. 22, No. 5 (May 1952).
71. "Determining the Position of Reinforcement in Concrete." *Engineering* (London), Vol. 175, No. 4555 (May 15, 1953) p. 640.
72. HOLTMAN, O., "Determination of Position of Reinforcing Bars" (in Dutch). *Cement* (Amsterdam), Vol. 5, No. 5-6 (June 1953) p. 80; *Proc. ACI,* Vol. 50 (Jan. 1954) p. 407.
73. DEN DAAS, H. C., "Controlling the Position of Reinforcing Rods in Concrete" (in Dutch). *Cement* (Amsterdam), Vol. 6, No. 15-16 (1954) pp. 227-229; *Bldg. Sci. Absts.,* Vol. 27, Abst. No. 1164, (Aug. 1954).
74. LORD, G. W., COUCH, R. W., and GOTHAM, D. E., "Location and Continuity of Reinforcement in Concrete." *Hwy. Res. Abst.,* Vol. 25, No. 4 (Apr. 1955) pp. 28-33; *Road Absts.,* Vol. 22, Abst. No. 797 (Oct. 1955).
75. VOLKER, F., "Geoelectric Measurements on Concrete Work" (Geoelektrische Messungen in de Betonbautechnik), *Zement und Beton* (Vienna), Vol. 1, No. 7 (Nov. 1956) pp. 11-16.
76. STRATFULL, R. F., "The Corrosion of Steel in a Reinforced Concrete Bridge." *Corrosion,* Vol. 13, No. 3 (Mar. 1957) pp. 43-48; *Hwy. Res. Abst.,* Vol. 27, No. 3 (June 1957) p. 6.
77. "Shrapnel Finder Spots Embedded Steel." *Eng. News-Record,* Vol. 159, No. 18 (Nov. 7, 1957) pp. 80-82.
78. YATA, Y., "Investigation of Reinforcing Bar in the Concrete by KETT Iron Detector" (in Japanese). *Semento Gijutsu Nenpo* (Tokyo), No. 12 (1958) pp. 434-440; Abst. (in English) in *Review of General Meeting* (Synposes) (1958) pp. 90-91.
79. PIHLAJAVAARA, S. E., "Locating Reinforcing Bars in Structures Using Non-Destructive Methods" (in Finnish). *Rakennusinsinoori* (Helsinki), Vol. 16, No. 2 (1960) pp. 40-45.
80. REBUT, P., "Non-Destructive Apparatus for Testing Reinforced Concrete: Checking Reinforcement with the 'Pachometer' " (in French). *Revue des Materiaux* (Paris), No. 556 (Jan. 1962) pp. 31-33.
81. MUSIL, F. J., "Eddy Current and Ultrasonic Technique for Inspection of Large Parts." *J. Materials,* Vol. 2, No. 1 (Mar. 1967) pp. 65-80.
82. MOORE, R. W., "Electrical Resistivity Instruments for Measuring Thickness and Other Characteristics of Pavement Layers." U.S. Bur. of Public Roads (1968).
83. MOORE, R. W., "Earth-Resistivity Tests Applied as a Rapid, Non-Destructive Procedure for Determining Thickness of Concrete Pavements." *Hwy. Res. Record No. 218* (1968) pp. 45-49.
84. MONFORE, C. E., "The Electrical Resistivity of Concrete." *J. PCA Res. Devel. Lab.,* Vol. 10, No. 2 (May 1968) pp. 35-48.
85. Personal correspondence from Woodrow J. Halstead, Chief, Materials Div., U.S. Bur. of Public Roads, to William G. Weber, Research Coordinator, Bur. of Materials, Testing and Research, Pennsylvania Dept. of Highways (Sept. 26, 1969).
86. LE ROLLAND, M., "Use of the Pendulum for the Study of Elastic Properties of Solids." *Non-Destructive Testing,* Vol. 8, No. 4 (Spring 1950) pp. 16-19; Abst. in *Eng. Index 1950,* p. 320.
87. HOEFFGEN, H., and BACK, G., "Experiences with Non-Destructive Testing of Concrete with Ball-Test Apparatus" (Erfahrungen über die Zerstörungsfreie Betonprufung mit Kugelprüfgeraten). *Bauingenieur* (Berlin), Vol. 26, No. 10 (Oct. 1951) pp. 297-300.
88. "Novel Concrete Tester." *S. African Municipal Mag.,* Vol. 35, No. 419 (July 1952); *Hwy. Res. Abst.,* Vol. 22, No. 10 (Oct. 1952).

89. GAEDE, J., *Ball Impact Testing of Concrete* (Die Kugelschlagprufung von Beton). Deutscher Ausschuss für Stahlbeton, Heft 107, Verlag Wilhelm Ernst and Sohn, Berlin (1952); No. 102 abridged translation, Library Abstract Ck. 3, Cement and Concrete Assn., Great Britain (July 1953).
90. GOGOBERIDZE, D. B., "The Pendulum Method of Measuring Hardness and the Relation Between Hardness and Surface Energy" (in Russian). *Trudy Inst. Fiz., Akad. Nauk Gruzin. S.S.R.*, No. 1 (1953) pp. 183-204; Referat, *Zhur., Fiz.*, Vol. 1955, No. 2829 (1955); *Chem. Absts.*, Vol. 50 (Mar. 10, 1956) p. 3030h.
91. BRADFIELD, G., and WOODROFFE, E. P. H., "Determination of Thickness of Concrete Pavements Using Mechanical Waves." *Report No. Phys./U5*, National Physical Lab., Dept. of Scientific and Industrial Res., Great Britain (Feb. 1953).
92. "Testing Concrete by Measuring Speed of a Shock Wave Through It" (in French). *Tech. Digests*, European Productivity Agency, Paris, No. 8, Digest No. 809 (Aug. 1958) pp. 97-98. Digested from Note Technique No. 9, Inst. Technique du Batiment et des Travaux Publics, Paris (1956).
93. HOCHSCHILD, R., "Microwave Non-Destructive Testing in One [Not-So-Easy] Lesson." *Materials Evaluation*, Vol. 26, No. 1 (Jan. 1968) pp. 35A-42A.
94. CANTOR, T. R., "Microseismic Non-Destructive Evaluation of Concrete." New York Port Authority (1968).
95. "Pavement Strength Analyzed Electronically." *Pub. Works* (Aug. 1969) p. 136.
96. Personal correspondence: "Detection of Concrete Deterioration Under Asphalt Overlays by Microseismic Refraction." From T. R. Cantor, Res. Engineer, Port of New York Authority, to W. G. Weber, Jr., Res. Coordinator, Pennsylvania Dept. of Highways.
97. HOWELL, L. G., and FROSCH, A., "Gamma Well Logging." *Geophysics*, Vol. 4, No. 2 (Mar. 1939) p. 106.
98. BRUNNER, E., and MARDOCK, E. S., "A Neutron Method for Measuring Saturations in Laboratory Flow Experiments." *Trans. AIMME*, Petrol. Div., Vol. 165 (1946) pp. 133-143.
99. BELCHER, D. J., CUYKENDALL, T. R., and SACK, H. S., "The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering." *Tech. Development Rept. No. 127*, U.S. Civil Aeronautics Admin. (1950).
100. SMITH, E. E., and WHIFFEN, A. C., "Density Measurement of Concrete Slabs Using Gamma Radiation." *Engineer* (London), Vol. 194, No. 5040 (Aug. 29, 1952) pp. 278-281.
101. FACKLER, J. P., "Concrete Testing with Gamma Rays" (Essais par rayons gamma sur les betons). *Cahiers du Centre Scientifique et Technique du Batiment* (Paris), No. 21 (Dec. 1953).
102. DEHAAS, E., "Radioactive Inspection of Concrete." *Ontario Hydro Res. News* (Canada), Vol. 5, No. 4 (Oct.-Dec. 1953) pp. 13-15.
103. WHIFFEN, A. C., "Location Steel Reinforcing Bars in Concrete Slabs." *Engineer* (London), Vol. 197, No. 5134 (June 18, 1954) pp. 887-888.
104. FORRESTER, J. A., "The Location and Identification of Reinforcement by Gamma Radiography." *Tech. Rept. TRA/274*, Cement and Concrete Assn., Great Britain (Aug. 1957).
105. FORRESTER, J. A., "Application of Gamma Radiography to Concrete." *Engineer* (London), Vol. 205, No. 5327 (Feb. 28, 1958) pp. 314-315.
106. MORAVIA, G., "Radiographic Examination of Reinforced-Concrete Structures" (in Italian). *Cemento Armato*, Vol. 55, No. 7 (1958) pp. 11-13; *Bldg. Sci. Absts.*, Vol. 32, Abst. No. 369 (Mar. 1959).
107. HONIG, A., "The Determination of the Position of Reinforcing Rods in Steel-Concrete Construction by Means of Radio-Active Isotopes." *Proc. Internat. Colloquium on Radio-Active Isotopes and the Construction Industry*, Leipzig (Sept. 1960).
108. POHO, E., "Density and Reinforcement Rod Studies of Concrete by Using Gamma-Ray Scattering." *Proc. Internat. Colloquium on Radio-Active Isotopes and the Construction Industry*, Leipzig (Sept. 1960).
109. KUNZE, G., "Experiences in the Determination of Tube Wall Thicknesses by the Gamma-Backscattering Method" (in German with English summary). *Isotopentechnic*, Vol. 1, No. 516 (May 1961) pp. 134-137.
110. SARNA, J., "Principles of Construction of a Thickness Gauge for Walls Accessible from One Side" (in Polish with English summary). *Rept. No. R-28;* In Pierwsze Krajowe Sympozjum Zastosowaii Izotopow w Tiechnice, Warsaw, Osrodek Informacji (1961).
111. POLIL, E., "Density and Reinforcement Investigations on Concrete" (in German with English summary). *Isotopentechnic*, Vol. 1, No. 516 (May 1961) pp. 138-140.
112. FORRESTER, J. A., "Gamma Radiography of Structural Concrete." *Final Rept. VI-3*, Sixth Cong. Internat. Assn. for Bridge and Structural Eng., Stockholm (1961) pp. 465-471.
113. HERRMANN, F. A., "Portable Thickness and Density Measuring Apparatus" (in German). *Kerntechnik*, Vol. 4, No. 7 (July 1962) pp. 282-285.
114. DIETZSCH, W., "The Measuring Sensitivity and the Measuring Error in Measurements of Thickness and Density with Radioisotopes According to the Irradiation Method" (in German with English summary). *Atompraxis*, Vol. 8, No. 4 (Apr. 1962) pp. 129-133.
115. BLACKWELL, P. L., "Impact of Nuclear Technology on Highway Engineering." *ASTM Spec. Tech. Publ. No. 373* (Feb. 1964) pp. 70-79.
116. "Determination of Air Content in Hardened Concrete by Gamma Ray Transmission." Michigan Dept. of State Highways (May 1967).

117. KONDO, O., and MARITA, M., "Non-Destructive Testing of Pavement Using Radioisotopes." Public Works Res. Inst., Japan (July 1968).
118. FOSTER, B. E., "Attenuation of X-rays and Gamma Rays in Concrete." *Materials Res. Standards,* Vol. 8, No. 3 (Mar. 1968) pp. 19-24.
119. DE CASTRO CUBELLS, V., "X-Ray Examination of Reinforced Concrete" (in Spanish). *Publ. No. 61,* Laboratorio Central de Ensayo de Materiales de Construccion (Madrid) (1949); Abst. in *Eng. Index 1950,* p. 239.
120. MULLINS, L., and PEARSON, H. M., "X-Ray Examination of Concrete." *Civil Eng.* (London), Vol. 44, No. 515 (May 1949) pp. 256-258; Abst. in *Eng. Index 1950.*
121. VIKTOROV, A. M., "X-Ray Photography of Concrete and Its Fillers" (in Russian). *Stroitel. Prom.* (Moscow), Vol. 31, No. 6 (1953) pp. 31-32; *Chem. Absts.,* Vol. 47, No. 21 (Nov. 10, 1953) p. 11691d.
122. RINALDI, G., "X-Ray Examination of Prestressed Concrete and Ordinary Reinforced Concrete Structures." *Beton- u Stahlbetonbau* (Berlin), Vol. 49, No. 4, pp. 88-92, Part I (1954); *Giornale del Genio Civile* (Rome), Vol. 92, No. 9, pp. 638-647, Part II (1954); transl. of Pts. I and II, Library Communication No. 751, Building Res. Station, Great Britain.
123. EVANS, R. H., and Robinson, G. W., "Bond Stresses in Pre-Stressed Concrete from X-Ray Photographs." *Proc. Inst. Civil Eng.* (London), Vol. 4, No. 2, Part 1 (Mar. 1955) pp. 212-235; Abst. in *Eng. Index 1955.*
124. "X-Ray Photography and Radiography of Concrete Structures" (in German). *Bauplanung Bautechnik* (Berlin), Vol. 12, No. 2 (Feb. 1958) pp. 82-83.
125. FOSTER, B. E., "Attenuation of X-Rays and Gamma-Rays in Concrete." *Materials Res. Standards* (Mar. 1968) pp. 19-24.
126. Personal correspondence from R. L. Grey, Supervisor, Physical Research and Development, Bur. of Materials, Testing and Research, to V. Worona, Asst. Engineer of Tests, Bur. of Materials, Testing and Research, Pennsylvania Dept. of Highways (Oct. 10, 1969).
127. SCHOLER, D. F., "Evaluation of the Performance of Ultrasonic Equipment for Pavement Thickness Measurement." Paper presented at 48th Annual Meeting, Highway Research Board, Washington, D.C. (Jan. 1969).
128. Walker, S., "Application of Theory of Probability to Design of Concrete for Strength Specifications." *NRMCA Publ. No. 57* (Nov. 1955) p. 5.
129. "Evaluating Procedures for Determining Concrete Pavement Thickness and Reinforcement Location." Interim Report, Phase I, NCHRP Project 10-8 (Dec. 1970).
130. MILLER-WARDEN ASSOCIATES, "Development of Guidelines for Practical and Realistic Construction Specifications." *NCHRP Rep. 17* (1965) 109 pp.
131. VESIC, A. S., and SAXENA, S. K., "Analysis of Structural Behavior of AASHO Road Test Rigid Pavements." *NCHRP Rep. 97* (1970) 35 pp.
132. DICOCCO, J. B., and BELLAIR, P. J., "Acceptance Sampling Plans for Rigid Pavement Thickness." *Res. Rept. 70-11,* N.Y. Dept. of Transportation (Apr. 1971).
133. WEBER, W. G., JR., and SMITH, T. W., "Practical Application of the Area Concept to Compaction Control Using Nuclear Gages." *Hwy. Res. Record No. 177* (1967) pp. 144-156.
134. BAKER, W. M., and MCMAHON, T. F., "Quality Assurance in Highway Construction, Part 3—Quality Assurance of Portland Cement Concrete." *Pub. Roads,* Vol. 35, No. 8 (June 1969) pp. 184-189.

APPENDIX A

LITERATURE REVIEW

INTRODUCTION

This literature review was conducted by the Pennsylvania Department of Transportation in preparation for the conduct of the research study NCHRP 10-8, "Evaluating Procedures for Determining Concrete Pavement Thickness and Reinforcement Position." The review was originally conducted in 1969 to obtain background information concerning the factors affecting the various methods which were planned for investigation. In 1970 after award of the NCHRP contract, this review was updated to include the latest information, and as a final search of potential methods of determining concrete thickness and reinforcement location.

The Literature Review is divided into five sections as follows:

1. Ultrasonic methods.
2. Electrical methods.
3. Mechanical methods.
4. Nuclear methods.
5. Other methods.

Over 1,000 publications were originally reviewed; however, only those that are most significant in each field are included in this report.

ULTRASONIC METHODS

Introduction

A wealth of information exists on the ultrasonic method of non-destructive testing. Only a small portion is included in the

References. Ultrasonic testing equipment for concrete thickness determination consists of a transducer arrangement that generates sound waves into concrete pavement. With the common method, the transmission time of the sound wave is measured and the result is indicative of the depth of the concrete. Several well-known electronic techniques are available for processing data from the transducers to give a digital readout of thickness, although no attempt has been made to incorporate such techniques in concrete measurements.

Several problems have been observed with the ultrasonic method. It is necessary for the transducers to generate a well-collimated beam of sound so that spurious signals will be minimized or eliminated. For such a desired collimated beam, it was discovered that the transducer design would have to be such that the ratio of the transducer diameter to the wavelength of the sound wave will have to be very large. Large mosaic transducers have shown an accuracy of ±2 percent in measuring pavement thickness. There also exists the problem of moving the transducers. Once the transducers have been removed from the concrete surface, it is virtually impossible to relocate them so that the degree of coupling remains the same. Another problem is the limitation of an upper frequency for the propagating waves; the limit is about 200 KHz.

The major detriment to widespread development of ultrasonic equipment for concrete pavement studies is the fact that this material is heterogeneous and a disperser so that most of the sound energy is absorbed or internally reflected. Also, roughness of subbase material produces uneven reflection of energy. The subbase also often has

acoustic properties very similar to the concrete under study so that meaningful reflections are often lost in noise.

Discussion

The history of ultrasonic methods for the non-destructive testing of materials can be traced as far back as 1889 when Chree investigated longitudinal vibrations (1).

In 1891 Sutherland published his "Kinetic Theory of Solids" (2); and shortly thereafter, Rayleigh wrote "The Theory of Sound" (3). These initial theories laid the foundations for the study and application of ultrasonics to non-destructive testing.

In 1928 crude transducers (magnetostriction oscillators) were developed (4).

In 1929 the sonic method was used to investigate stresses in buildings (5).

In 1932 the acoustic method was applied to concrete structures, particularly dams, to determine stresses (6).

In 1935 a vibration method was used to determine Young's Modulus for building materials (7). A comparison to determine statically and dynamically Young's Modulus of rock was made in 1936 (8). Induced vibrations were used in 1939 to investigate highways (9). During the same year, Hornibrook applied the sonic method to freezing and thawing studies of concrete (10); and Meyer and Bock used sonic and ultrasonic methods in the testing of concrete beams that were cracked (11). Meyer, at the same time, applied the ultrasonic method to the testing of setting cement (12).

In 1940 the sonic method was applied to concrete to measure the change in its physical properties (13).

In 1945 an instrument and a technique for field determination of the modulus of elasticity and flexural strength of concrete was developed (14).

A new electro-acoustic transducer was developed in 1948 that operated with short pulses (15). Also, during this year, research in London was completed by Jones on the application of ultrasonics to the testing of concrete (16).

In 1949 dynamic testing of concrete was accomplished with a device called the soniscope (17). During the same year, in London, Jones measured the thickness of concrete pavements by sonic methods (18); and Van Valkenburg wrote "The Theory of Ultrasonic Materials Testing" (19).

In 1950 the works of Leslie and Cheesman gave great impetus to the study of ultrasonics (20, 21, 22). Further development of transducers occurred as Mason applied piezo-electric crystals to ultrasonics (23).

In 1951 Whitehurst used the soniscope, an instrument which measures group velocities through as much as 50 ft of concrete, to field test 13 bridges, several navigation locks, 14 dams, and five highway pavements in 12 states. The change in group velocities during repeated tests showed corresponding changes in the condition of the concrete. The results of measuring group velocity through concrete showed the technique applicable to the study of concrete in field structures. This technique did have some limitations in that the soniscope measured only one property of concrete (improvement or deterioration) and the interpretation of other properties often led to incorrect conclusions (24). Other published works during 1951 by Whitehurst were concerned with applications of the soniscope (25, 26). Also in 1951, a method of measuring longitudinal wave velocity was described by Jones. Laboratory applications of this method included the use of the ultrasonic technique in studies of the setting of concrete, freezing and thawing, and the determination of Poisson's Ratio (27).

In 1953, Dawance and Blanc made several contributions to the field of ultrasonics by investigating transverse propagating waves. They also studied the quality of concrete by measuring the velocity of the propagating waves (28, 29, 30).

In 1954 French engineers proposed a procedure to determine the quality of concrete by a sonic method which measured the velocity of propagation of an elastic wave. Subsequently, the modulus of elasticity and Poisson's Ratio of the concrete, both functions of density, on specimens up to 1 meter thick were determined within an accuracy of 1 percent. It was proposed that the method of testing could also be used to locate cracks in concretes, determine concrete quality, locate aggregates, determine quality of construction joints, and determine the quality of bond between concrete and reinforcement. The main advantage advocated here was the possibility of testing these materials under adverse conditions (31). Other research that was conducted during 1954 involved the determination of some mechanical characteristics by acoustical methods (32), the measurement of depths and widths of concrete cracks by ultrasonic test methods (33), and an investigation into the problems of sonic testing of concrete (34).

Advances that occurred in 1955 through the use of ultrasonic testing were the prediction of the rheological behavior of concrete (35), measuring thickness of concrete road slabs in-situ (36), sound energy attenuation measurements (37), determination of damage in reinforced concrete constructions (38), and the development of a portable ultrasonic concrete testing apparatus (39).

In 1956 Chang and Kesler correlated the sonic properties of concrete with creep and relaxation and were able to predict the creep behavior of concrete from its sonic properties (40, 41). Also in 1956 the development of a new soniscope was announced (42).

During 1957 Jones discussed the unreliability of velocity-strength correlation and the difficulty of measuring path length taken by the sound waves. He did, however, cite several practical applications of ultrasonics, including quality control, determination of setting time, and location of cracks (43).

In 1958, more work was presented with regard to the use of ultrasonic in appraising the quality and performance of concrete (44).

In 1959, a report summarized eight years of pulse velocity tests on concrete pavements in Kansas. The conclusion reached was that no reliable relationship between pulse velocity and flexural strength of concrete was apparent at that time (45). Other research that year was conducted on the attenuation constant of the ultrasonic wave (46) and on the resonant frequency method of test (47). In Berlin at this time an analysis was attempted concerning the elastic properties of concrete using ultrasonics (48).

In 1961 the ultrasonic method was described in testing a bridge pier (49), in analyzing the quality of cementation of borehole casings (50), and in studying the relationship between compressive strength of concrete and the longitudinal ultrasonic velocity (51).

In 1963 Muenow described a technique for determining the thickness of concrete slabs by non-destructive means employing an ultrasonic apparatus (52). The results of ultrasonic tests were compared with the measured thickness of cores taken from the same locations. It was claimed that this non-destructive technique of measurement was within 5 percent of the measurement of a core taken from the same location. The technique also possessed the advantage of speed and ease in making tests.

In France during 1965 dynamic auscultation was used as a method for controlling the quality of concrete. Other determinations resulting from the auscultation method were Poisson's Ratio, compressive strength, and cleft and cavity determinations (53).

In 1965, Jones and Mayhew described the surface wave method as a non-destructive testing technique for calculating the thickness and the elastic properties of a layer of material and for estimating the in-situ quality of the material (54). Also in 1965, the method was applied to highway testing studying 40-foot pavement length at a time. The wavelength and velocity of the vibrations were determined, and results obtained were converted to strength. Other detections or measurements made included the weak areas in the cemented granular bases, inadequate compaction, and the equivalent thickness of the concrete (55).

Research was conducted over a two-year period, ending in December 1966, on the development of a prototype thickness gage. The gage showed accuracies better than ± 2 percent in determining highway pavement thickness. The developments that led up to the modified pulse-echo technique were described, and a projection for the future use of this method was made (56). The potential uses of sonic and ultrasonic devices were also projected by Moavenzadeh and McMaster in 1966 (57). Sonic testing of materials was conducted in France during 1966, and practical information obtained from the results was supplied (58).

In 1967 the Texas Highway Department conducted a study to develop a non-destructive method of measuring thickness of concrete pavement using ultrasonic devices. The difficulty in the design and assembly of such a device was believed due to the complexities of transducer development. No practical instrument was developed, but a detailed explanation of progress achieved by the study was included (59).

In the same year, a tentative method of test was proposed by ASTM. The method consisted of measuring the time of travel of a pulse or train of waves through a measured path length in the material. This travel time was related to the condition of the concrete. This method, however, was not to be considered an index of strength nor as an adequate test for establishing the compliance of the modulus of elasticity of field concrete with that assumed in design (60). Also in progress during 1967 in Denmark were ultrasonic pulse velocity measurements applied to green concrete with the aim of studying early curing (61).

In 1968 three different techniques were recommended in NCHRP Report 52 for thickness measurement. One recommendation was the use of large mosaic transducers with an estimated accuracy of ± 2 percent. These could be used on any type of pavement up to 10 in. in thickness and under any conditions. Units described were suitable for operation by an unskilled technician and yielded a digital readout of thickness if required. The prototype was designed but had not yet been constructed. A smaller model employed gave an accuracy of ± 2 percent but had poor beam collimation due to its small size (62). Research was completed by Riffle in 1968 on the quality control of materials in the laboratory and field by ultrasonic testing techniques (63). A study in India used the ultrasonic method to detect air content and honeycomb in concrete. It was concluded that this method would be impractical in the field (64). Also in 1968, the New Jersey Department of Transportation utilized ultrasonics to test the thickness and the structural integrity of concrete slabs and decks (65).

The Ohio State University developed an ultrasonic instrument to measure pavement thickness. Problems encountered included identifying the correct signal in the measurement of the thickness of hardened pavements, determining the optimum transmitter and crystal frequency, and measuring the acoustic velocity (66).

A study concerning world-wide research on non-destructive testing, including the use of ultrasonics, has been reported by Jones, Harland, Lister, and Thrower (67), showing that although ultrasonics have been studied, conclusive justification remains to be established before acceptance of the method.

ELECTRICAL METHODS

Introduction

Two uses of electrical methods were discovered: 1) to locate reinforcement by inductance method, and 2) to determine pavement thickness and reinforcement depth by concrete resistance measurements.

The inductance method resulted in the development of the pachometer for determining the location and depth of reinforcement. This equipment has been in use for several years with satisfactory results reported. It operates on the principle of the change in inductance of a coil by the presence of steel. The reports indicate that the location, depth, and size of reinforcing steel may be determined with this equipment in plastic or hardened concrete.

The possibility of utilizing the resistivity method used in geophysics has been reported. The results indicate that reinforcement depth and thickness of the concrete may be determined. As only limited work has been reported with this method, its limitations are not clearly understood. However, the area of contact with the concrete will affect the readings. Its use in plastic concrete has not been fully studied. However, the limited work performed indicates that this method has considerable promise. The size and horizontal location of reinforcement can not be determined by this method.

Discussion

The coming of World War II necessitated the development of an electrical device for the effective detection and removal of metallic foreign bodies during surgery. Such a device, known as the Berman

metal locator, was developed by Samuel Berman and put into use immediately in 1941. The machine has been used extensively by the U.S. Army Medical Corps and the medical profession in general since that time. Needing a method to determine the presence or absence of reinforcing steel in concrete, the Washington District of the Corps of Engineers discovered and put into use the Berman metal locator. They found the machine simple to operate and very useful in the location of reinforcement in concrete structures (68).

In 1951 an apparatus called the "covermeter" was developed for the measurement of the depth of reinforcement below the surface of hardened concrete (69). The covermeter was designed for either laboratory or field use primarily for determining the depth of steel reinforcement. It could find the location of the reinforcement with considerable accuracy (70). A portable electronic instrument that located reinforcement and indicated its depth was described in 1953 (71). The location of reinforcement in concrete was the object of more research by Holtman in 1953 (72), by Den Daas in 1954 (73), and by Lord, Couch, and Gotham in 1955 (74). In 1956 an electrical non-destructive testing method employing electric potential fields was used to determine the distribution of various materials, both horizontally and vertically. With this method, it was possible to locate cracks and to determine the thickness of concrete (75). The electrical method was also applied in a study to determine the cause of accelerated corrosion of reinforcing steel in a concrete bridge. Charts indicated that the resistivity of concrete decreases as the deterioration of the concrete increases (76). The use of the Berman metal locator as an embedded steel finder was again reported in 1957 (77).

Reinforcing bars in concrete were investigated in Japan in 1958 with an instrument called the "KETT iron detector" (78). Again in 1960 the location of reinforcing bars was investigated using electrical non-destructive methods. Covermeters (electro-magnetic instruments) were deemed useful and inexpensive in observing concealed features in reinforced concrete (79).

A new device called the "pachometer" was discussed in 1963 as a possible non-destructive apparatus for checking reinforcement in concrete (89). A laboratory study was conducted in 1967 to determine the feasibility of replacing the destructive methods of inspecting machined parts and thin walled cylindrical tanks with a non-destructive eddy current technique. The eddy current system was capable of inspecting large parts (26 by 10 ft) in approximately 50 percent less time than the previous destructive methods. The technique for measuring the length and depth of discontinuities with a rotating eddy current probe was discussed by Musil (81). Electrical resistivity tests were adopted for the determination of the thickness of concrete pavement by Moore in 1968. The results of 150 tests were encouraging; but more testing was deemed necessary to determine the effectiveness of the proposed test procedure under all field conditions (82, 83). An investigation of the electrical properties of concrete was conducted by Monfore in 1968. This study showed that moist concrete is essentially an electrolyte and that oven-dried concrete is a reasonably good insulator (84). Further information concerning Moore's research on the measurement of pavement thickness by an electrical resistivity method indicated that the method will be applicable to both hardened and plastic concrete for both plain and reinforced slabs (85).

MECHANICAL METHODS

Introduction

The thickness of hardened concrete may be determined by the production of a seismic wave by mechanical impact. The seismic wave impulses are detected by an ultramicrometer. This method is similar to the ultrasonic method with many similar limitations.

Discussion

The mechanical phase of non-destructive testing has only been investigated and employed as a testing method during the last two decades. The earliest investigation of mechanical devices specifically for non-destructive testing occurred in 1950 when a pendulum was used for the study of the elastic properties of solids (86). The experiences with a ball test apparatus in Berlin were recorded in 1951 (87).

In 1952 a Swiss engineer, Ernest Schmidt, introduced a novel instrument that was to become the cornerstone of mechanical non-destructive testing development. The instrument measured the compressive strength of concrete by indicating the amount of rebound of a spring-propelled hammer. The rebound hammer was a quick and efficient test for concrete in the field with a claimed accuracy of 15 to 20 percent of actual strength (88).

Methods investigated in 1953 were the ball impact method of testing concrete (89), the pendulum method of measuring concrete hardness

(90), and the mechanical wave method of determining concrete pavement thickness (91).

New to the mechanical non-destructive testing scene in 1956 was a method of testing concrete for hardening, strength, homogeneity, flaws, and effect of frost by measuring the velocity of propagation of a mechanically increased shock wave generated through the concrete (92).

Microwave non-destructive testing was applied in 1968 to flaw detection; to measuring distance, displacement, dimensions, contour, vibration, and thickness of non-metals and metals; and to monitoring moisture content, degree of cure, chemical composition, and orientation (93).

A mechanical method of non-destructive testing was recommended in NCHRP Report 52 in 1968 for the measurement of pavement thickness. This method employed short mechanical impulses that were detected by an ultramicrometer (accuracy ± 2 percent). It could be used on any type of concrete pavement in the hardened state. Operation could be performed in 30 seconds by a semi-skilled technician with satisfactory results. However, weak received signal strengths made the system vulnerable to spurious signals on occasion (62). Microseismic non-destructive evaluation was also conducted by Cantor in 1968 (94). Another mechanical device was utilized in 1969 in applying a sinusoidal load, similar in size to that of a loaded truck tire, to a pavement surface. Wave velocities were determined and used to calculate the elastic moduli of materials for the pavement layers (95). Also in 1969, tests were performed to detect concrete deterioration under asphalt

overlays by microseismic refraction. This method was thought to be suitable for the routine monitoring of concrete base slab conditions over large portions of asphalt overlaid structures, and for the determination of asphalt thickness without disturbance of the material (96).

NUCLEAR METHODS

Introduction

Nuclear non-destructive testing apparatus are currently being used to measure density, moisture content, asphalt content, and thickness of concrete pavement. Devices developed employ either direct transmission or the backscatter technique. Both techniques require a radioactive source that emits gammas or neutrons and a detector that is sensitive to them. A count of gammas or neutrons arriving at the detector per minute is an indication of the density, moisture, asphalt, or thickness of the concrete after proper calibration.

It was noted that a direct method for the measuring of pavement thickness involved the scattering of radioactive pellets before placement of the pavement. After the concrete is poured over the pellets, a detector is positioned directly above a pellet, and the counts obtained are related to the depth of the concrete cover. Nuclear testing equipment is calibrated using known standards and methods so that the counts obtained may be translated into a measurement of pavement thickness before the concrete has cured.

Discussion

Nuclear methods for the non-destructive testing of materials were applied as early as 1939 in the examination of the strata in bored holes

movement of aggregate particles appeared promising (104, 105). The same method was used by Moravia in the examination of other reinforced concrete structures (106).

In 1960, radioactive isotopes were employed for the determination of the position of reinforcing rods in steel concrete construction (107) and for density studies (108).

Investigations were conducted in 1961 with a nuclear gage for the determination of tube wall thickness (109) and for the determination of the thickness of walls accessible from only one side (110). Density and reinforcement investigations were also conducted in 1961 on structural concrete (111, 112).

The development of a portable thickness and density apparatus was an innovation for the field testing of concrete (113). The sensitivity and the measuring error of this type device were determined and recorded by Dietzsch in 1962 (114).

The impact of nuclear technology on highway engineering was recorded in 1964 (115).

Attempts were made in 1967 at determining the air content of hardened concrete by a nuclear-type non-destructive method. It was discovered that conventional destructive methods of test were more satisfactory than this overly sophisticated method (116).

Radioisotopes were employed again in 1968 to determine the densities of each layer of a concrete or asphalt slab (117). To enable the technologist to understand more fully gamma ray attenuation in concrete, Foster furnished a paper that described the elementary workings of such a system (118).

(97). Other early applications of radioactivity included the measurement of the amount of oil saturation in cores (98) and the measurement of soil moisture and density (99).

Nuclear testing methods were not applied to the non-destructive testing of concrete until 1952. The method was based on gamma radiation absorbed by concrete. A tube of radio-cobalt was lowered into a bored hole in a concrete slab, and the measurement of the amount of gamma radiation absorbed by the concrete gave an accurate indication of the concrete density (100). This same test was repeated in 1953, and variations in density were determined with a 1 percent accuracy in concrete mixes (101).

Limitations were placed on the use of radioactivity for the inspection of concrete by DeHaas in 1953. He stated that it was undoubtedly infeasible to measure a width of concrete greater than 3 ft. Also, there existed a need for a two-face exposure of the concrete being tested. The greatest advantage of the system was that it could be used while the concrete was still plastic (102).

An experiment was conducted in 1954 using gamma radiography to locate accurately the position of reinforcing bars in 6-in.-thick slabs of concrete. Cost of equipment was low; operation was simple and safe; and results were accurate (103).

In 1957 and 1958 Forrester described a method concerning the location and identification of reinforcement in concrete by gamma radiography. He stated that this non-destructive, and relatively inexpensive, method for determining the location and condition of reinforcing bars, the condition of the concrete, and the effect of vibration on the

A nuclear non-destructive method was highly recommended by NCHRP Report 52 for pavement thickness determinations. This technique consisted of scattering radioactive pellets prior to the laying of pavement. The pellets were safe and inexpensive, and the system had an estimated accuracy of ± 1 percent. The pellets could be placed under any type of pavement under various conditions. The system was simple, reliable, and suitable for operation by an unskilled man with a measuring time of a few minutes. However, it could not be applied to existing roads and continuous measurement of thickness was not possible although frequent spot checks could be substituted (62).

OTHER METHODS

Introduction

The X-ray method of non-destructively testing concrete is infrequently used because the required equipment is far too bulky and expensive for the accuracy it provides. Industry, however, does utilize the X-ray method for inspection and control. More appropriate methods are available for the locating and identification of steel reinforcement in concrete.

The microwave thickness gage is a new innovation for the measurement of concrete thickness and reinforcement placement, and present research indicates that the gage will be applicable to these areas when the state of the art has advanced.

Discussion

X-ray.--As a result of the improvements of production and detection of X-rays after World War II, the X-ray technique has been used

extensively to control the thickness of many materials. However, applying the technique to the non-destructive testing of concrete requires elaborate equipment and many safety precautions that lead to great expense and bulk.

In 1949 the X-ray method was utilized in the examination of reinforced concrete in Spain (119) and in the examination of plain concrete in England (120). X-ray photography was performed on concrete and its fillers in the Soviet Union in 1953 (121). In 1954 the X-ray non-destructive testing technique was used in the examination of prestressed concrete and ordinary reinforced concrete structures (122). X-ray photography was used in analyzing bond stresses in prestressed concrete in 1955 (123) and other concrete structures in 1958 (124).

X-ray attenuation in concrete was the topic of a research program in 1968. A method of calculation for X-ray attenuation in concrete was developed, and procedures were considered adequate (125).

Microwave.--Prototypes of a microwave thickness gage were developed in 1969 to read the thickness of concrete and reinforcement placement non-destructively on newly placed or fully cured concrete. The gages utilized the radar principle and showed favorable results. The model could detect concrete thickness to about 6 in. with an accuracy of one-quarter in. It was claimed that new developments would allow the device to detect readily depths in the 10- to 12-in. range with better than ¼-in. accuracy. The entire unit was portable, self-contained, battery powered, and simple to operate (126).

APPENDIX B

INSTRUMENT SELECTION AND PRELIMINARY EVALUATION

INTRODUCTION

It was the intention in this project to evaluate as many as possible of the techniques for thickness determination suggested in NCHRP Report 52, "Measurement of Pavement Thickness by Rapid and Non-destructive Methods" (62). The instruments or methods, however, had to be proven and available either as tested prototypes or commercially produced gages. Fifteen manufacturers and six agencies were initially contacted for information concerning the availability of devices either discussed by previous literary references or mentioned by manufacturers during past personal contact.

After the availability of the instruments had been assessed, those which could be obtained in time for the project were tested in the field. The following discussions describe the mode of operation of the instruments, along with relevant observations and recommendations resulting from the initial testing program and subsequent field studies.

DISCUSSION

The Ultrasonic Gages

Two devices which utilize the ultrasonic wave propagation technique for thickness determination were chosen, due to their current status as workable instruments either commercially available or beyond the prototype stage. Although the systems used the same basic principles of operation, the actual techniques of thickness determination differed.

The first ultrasonic device (designated hereafter as the ultrasonic-1 gage) uses two separate piezoelectric transducers which can be spaced at any distance apart on the pavement (127). In this system, one transducer acts as a transmitter of ultrasonic energy at a particular frequency and pulse rate, and the second transducer acts as a receiver. Pulses of ultrasonic energy are transmitted into the material under test; and the second transducer, spaced some distance apart from the transmitter, receives the transmitted signal. This signal is then displayed on an oscilloscope, along with an initial pulse indicating the time at which the signal was transmitted into the pavement. The time, in microseconds, between the initial pulse and the received signal is shown digitally with the apparatus. This time, and the spacing between the transmitting and receiving transducers, is known; hence, the velocity of the sound can be calculated.

This instrument employs the classical equation to determine thickness, as suggested by the manufacturer.

$$\text{thickness} = \frac{\text{velocity}}{2 \times \text{resonant frequency}}$$

Field use of the ultrasonic-1 gage requires an inverter to provide proper AC voltage. The inverter must generate nearly perfect sine wave voltages for proper operation of the instrument. However, most normally available inverters do not generate sine wave voltages and cause the gage to perform improperly.

Although only a slight amount of couplant is necessary between the transducers and the pavement (1 ounce per test), care must be taken to insure that no air voids exist between the crystals and the concrete;

otherwise, erratic results occur. The transducers have to be forced into intimate contact with the pavement, as well, to yield a response of discernible amplitude. Thus, two operators were required for a test, one at the transducers and one at the readout.

It was often difficult to select the point on the readout at which the transmitted sound was received. The instruction manual indicated that the beginning of the first deviation from a horizontal line should be chosen, but there was often a very slight wave form apparent before the major wave. All data taken for velocity readings, therefore, include these minor changes in wave form as well as the first major deviation from the horizontal.

The instruction manual further states that resonant frequency should appear as a Lissajou circle, preceded by an ellipse 45 degrees to the right of vertical and followed by a second ellipse 45 degrees to the left. Multiple circles occurred frequently. These often showed a left-circle-right configuration, which would be impossible, since this would indicate above-at-below frequency, although the frequency was being increased at the time the sequence appeared. It is apparent that the transducers themselves have resonant frequencies, which appear along with the concrete resonant frequencies. The data recorded include both the frequency at which the first circle appeared and the frequency at which the proper phase sequence appeared. Subsequently, data analyses were made to find the velocity and resonant frequency signals for optimum test results. It was found that the first slight wave form change was the proper indication of velocity, while the second Lissajou circle--the one

in which the proper phase sequence occurred--was the best indication of resonance.

Temperatures of both air and pavement had a considerable effect on the ultrasonic-1 gage. It proved meaningless, for example, to test at pavement temperatures in excess of 110° F--temperatures common during the testing program. The system did incorporate an internal calibration check which was checked at daily intervals. This calibration varied only slightly over the entire testing program. The instrument is shown in Figure B-1.

The second ultrasonic device (hereafter designated as the Ohio State ultrasonic gage) was a development of research conducted at The Ohio State University (66). This instrument is similar to the Ultrasonic-1 gage, with the exception that the transducers employed are much larger and are capable of transmitting high power signals into the concrete under test. The sending transducer is actually an array of transducers arranged in a doughnut shape, approximately 18 in. in diameter, while the receiving transducer is approximately 2 in. in diameter. The latter transducer is placed in the open center of the circular array of the transmitter and detects the ultrasonic pulse reflected from the slab-subbase interface. The received signal is displayed on an oscilloscope, resulting in the determination of time-of-flight for the ultrasonic pulse from the surface of the concrete to the subbase and back to the surface. The thickness of the concrete slab can readily be calculated from this time-of-flight measurement, the geometry of the test setup, and a separate velocity determination, using the transducers and the technique described for the Ultrasonic-1 gage.

B-5

The transducers are AC powered and require large amounts of liquid couplant (1 pint per test) which leave extensive areas of the pavement rather unsightly after testing. An inverter-equipped vehicle is used to provide a portable power system.

Relatively trouble-free operation was experienced with the Ohio State ultrasonic gage in the later field studies. The most important problem occurred when the reflected signal was obscure or absent--several minutes might be spent searching for the signal. Although there were several major equipment failures, these were rectified by the operating personnel in no more than one day.

The system utilizes standard laboratory electronic equipment, resulting in the problems of temperature, moisture, and voltage control, normally encountered when such equipment is subjected to a field environment. The system in operation is shown in Figure B-2.

Pachometer

The pachometer is designed specifically to detect steel reinforcement location and size. It has been commercially available from a midwestern electronic firm, for several years. Although several similar gages are available commercially, this instrument was chosen for the project as it was the only one known to be capable of detecting steel at depths greater than 3 in., with the added capability of predicting bar size as well as depth.

Fundamentally, the pachometer is an electromagnet, with a meter deflection dependent upon the completion of a magnetic circuit to the buried steel reinforcement. The system is self-contained, battery-operated, and weighs approximately 5 lb.

B-6

Initial laboratory tests with the pachometer indicated that the calibration curve supplied by the manufacturer was in question. Therefore, a calibration was developed by suspending steel reinforcement bars over the gage and noting the instrument readings. The bars were suspended from 1/8 in. over the probe to 7 in., in 1/8-in. intervals. Calibration was done for all common bar sizes, from No. 3 through No. 10. This calibration should be valid when concrete is between the steel and the probe, as concrete is "invisible" to the device if the aggregate does not contain ferrous materials.

The calibration was found to be semi-logarithmic, with ample sensitivity to a depth of about 4 in. Below 4 in., the response is virtually independent of bar diameter, and considerable care must be taken to establish a valid reading since this portion of the calibration is very flat. Any misreading will inject large errors into the depth determinations.

Calibration for 4- and 6-in. wire fabric was accomplished in the same manner, and to the same degree of sensitivity, as for bars. It should be noted that the reading for this gage is always of depth to the top of the steel bars or mesh, not to the center, as is usually determined in physical measurements of reinforcement depth.

Readings can be made immediately after placement of concrete, as long as care is taken to prevent the probe from penetrating into the wet pavement. Operation of the pachometer is trouble-free. The five 1-1/2-volt dry cell batteries, powering the unit, were replaced twice during 12 weeks of field testing. The pachometer in operation is shown in Figure B-3.

B-7

Eddy Current Proximity Gage

The eddy current proximity gage (ECPG) was loaned to the project by the National Aeronautics and Space Administration, through the George C. Marshall Space Flight Center, Huntsville, Alabama. The inventor, Mr. R. Brown, Sr., had been contacted by PennDOT after a review of a NASA technical brief on the device. Although the instrument was still in the prototype stage, its promise of high sensitivity and low cost made it desirable to include it in the project.

The ECPG operates on the eddy current principle, whereby a ferrite core antenna radiates a low power radio frequency into the material under test. Power loss due to eddy currents induced in an aluminum plate or foil is detected by a second receiver antenna in a bridge network with the transmitting antenna. The differential output of the receiver is amplified and displayed on a microammeter.

A workable model of the eddy current proximity gage was not received from NASA until all test slabs had been placed. Prior discussions with the inventor, however, led to the placement of aluminum plates or foil on the subbase before concrete was poured for the test slabs. A total of eight plates, 1 ft square by 1/8 in. thick, were placed under Slabs A and C, and eight 2 ft-square test sites on Slabs E and H were underlain by 14-in.-square sheets of commercially available aluminum foil (see Appendix C).

Calibration for this prototype device had to be developed prior to testing. Aluminum plate and foil materials were placed at 1/2-in. intervals from the gage, up to a distance of 15 in., and the reading recorded. Curves of spacing versus reading were plotted from these data.

B-8

The calibration curves were found to be semi-logarithmic, with the maximum slope change between zero and 8 in. At depths greater than 8 in., great care is needed in arriving at a valid reading since a slight reading error can result in a large error in depth determination. In this way the eddy current proximity gage resembles the pachometer.

The response of the gage was observed to drift somewhat, making it necessary to re-zero the instrument before and after each reading, during the calibration, for uniformity of results. This re-zeroing was done by pointing the detecting end of the instrument away from any metallic objects. It was noticed at this time that the gage was affected by larger ferrous objects. At high ambient temperatures, the drift tended to increase and the reading became erratic. With the exception of the problem of drift, the eddy current proximity gage functioned quite well in the field testing portion of the project.

Figure B-4 shows the eddy current proximity gage in operation.

The Resistivity Gage

A resistivity gage had been previously built by PennDOT in general conformance to that discussed in a report by Moore (83). This method of test relies on the theory that electric current generated by two probes spaced a known distance apart on a material under test results in equipotential bowls of radii equal to one-third the distance between the probes. By placing two electrodes between the two generating currents at the points where the equipotential bowls intersect with the material surface, it is possible to measure the potential change which occurs at a given depth beneath the material surface. By increasing the distance between electrodes, while still maintaining the four electrodes at equal distances apart, resistivity readings can be computed for a series of spacings. When the equipotential zones are increased due to electrode spacing, and resistivity readings are taken at each spacing, a point of material change--such as subbase beneath the pavement--will register a different electrical resistivity. A plot of the individual and cumulative resistivities versus equal spacing, as suggested by Moore, predicts the depth to the material producing a change in resistivity. With this technique, it would also be possible to detect reinforcement depth in the pavement, due to the enormously different resistivities of concrete and steel.

In the modified equipment built by PennDOT, the number of probes was increased from 4 to 48, spaced 1 in. apart. For point contact and surface wetting action, these probes are hypodermic needles filled with a copper sulfate gelatine solution. By use of an earth resistivity bridge readout device and push-button switches, spacing can be selected automatically, instead of physically moving the probes. As a result of these modifications, the instrument is capable of reading to a depth of 15 in. in approximately 5 minutes, or roughly one-fourth of the time required by the original instrument.

In using this method, the copper sulfate gel in the probes must be given sufficient time to permeate the concrete surface. Otherwise, infinite resistance readings result. Laboratory tests on calibration blocks revealed that meaningful results are obtained only from surfaces properly wetted by the electrolyte. It was noted early in the testing program that the most rapid results were obtained on freshly poured concrete or slabs wetted by rain. This may have been a function of the

small contact area presented by the hypodermic needles used as probes.

A major difficulty with the resistivity method lies in interpretation of the test results. Slope changes in the data plots, indicative of material differences, are often so minor that only an individual carefully trained in the technique can validly choose the points of inflections. In effect, the pavement design thickness must be known beforehand to aid in detection of the inflections. While the technique may have some merit in new construction, it is questionable whether it could be applied to existing pavements, where the designed thickness is not known.

The modified resistivity equipment in operation is shown in Figure B-5.

The Mechanical Impact Gage

A mechanical impact gage was fabricated along the lines of the device discussed in NCHRP Report 52 (62). In theory, a mechanical shock induced in the hardened pavement will create a shock wave in the concrete, which will then be reflected by the concrete-subbase interface and returned to the surface. By means of a very high output, miniature crystal force transducer (shown in Figure B-6), the reflected pulse is received on an oscilloscope, along with a reference pulse to indicate the precise initiation of mechanical impact.

The spacing of the transducer from the point of impact is known; and three definite pulses are needed to interpret the data for pavement thickness. A round-tipped rod, 18 in. long and 1/8 in. in diameter, is fired onto aluminum foil placed on the pavement. The rod and foil are

electrically connected, forming a switch; and the initial pulse is triggered on the oscilloscope at the precise moment of impact. The second pulse should appear on the oscilloscope when the surface shock wave reaches the transducer, and the third pulse should appear as the shock wave is reflected from the subbase. Typical oscilloscope outputs are shown in Figure B-7.

Although in laboratory testing the transducer chosen proved very reliable and extremely sensitive and the first two pulses were readily seen on the photographs of the oscilloscope output, the most important third pulse was not discernible. Therefore, this method was not tested in the field.

The Nuclear Gage

A prototype nuclear gage, conforming to the theoretical model described in NCHRP Report 52 (62), was purchased for this project from a west coast manufacturer of nuclear soil density-moisture gages. The system is basically a sodium iodide crystal coupled to a photomultiplier and single channel pulse-height analyzer, with the final count displayed digitally, and also on a count-rate meter. The detector can be raised, from surface level to 14-1/2 in. above the surface, by a vernier screw drive which displays the height raised, digitally, to the nearest 0.01 in.

According to previous theoretical work described in the NCHRP report, a radioactive pellet placed on a subbase prior to paving emits radiation which can be detected on the concrete surface. The count of gamma rays of a selected energy is a function of detector area,

radioactive source strength, the linear absorption coefficient of the material tested, and the distance from source to detector. Counting for a set period of time on the surface and then raising the detector until the count is one-fourth of that on the surface, should predict pavement thickness since, theoretically, the height at which the count equals one-fourth the surface count is the thickness of the pavement.

Another technique for thickness determination, using the nuclear gage (suggested by Atomic Energy Commission personnel), relies on the use of scandium 46 for the radioactive pellet. This source radiates two predominant gammas in the same relative quantities, 0.89 MEV and 1.12 MEV. In this technique, counts of 1.12 MEV gammas are taken on the surface of the concrete, as is done in the first method; then the pulse height selector is changed to count the 0.89 MEV gammas. Since the absorption of the higher energy gammas is less than that of the lower, a ratio of the two should be a function of the thickness of the concrete.

The gage used was self-contained and battery-powered. The batteries permitted approximately 6 hours of continuous use before recharging was necessary. The nuclear gage is shown in Figure B-8.

The gage was operated in laboratory and field tests in accordance with the manufacturer's recommendations. Radioactive sources of scandium 46, of 10 microcuries activity each, were obtained from the Oak Ridge National Laboratory, after an isotope license was received from the Atomic Energy Commission. These sources were sealed in a thumbtack-shaped capsule (see Figure B-9) for ease of installation into the subbase.

A problem was encountered in precisely locating the source after the concrete was in place. The statistical nature of the radiation caused the ratemeter to vary sufficiently to necessitate several 1-minute counts in the vicinity of the source before a precise location for the gage could be determined. Thus, considerable time might be lost before an actual test can be run. The gage was operated daily with only minor equipment breakdowns. The battery was recharged overnight.

Tests on the slabs often produced questionable results, such as a count increase with increased height of the detector above the pavement surface. It was felt that adjacent sources might be affecting the count. Three alternative procedures were tried in an attempt to correct this problem: sources were more widely separated, multiple sources were used in selected test locations, and an attempt was made to collimate the radiation at a number of test locations by using a 3/4-in.-high stack of lead washers with a 5/16-in. center hole. None of these changes resulted in significant increases in sensitivity of the nuclear method. Also, an attempt was made to discover why the gage was not operating according to the inverse square law of radiation theory. Counts were taken over a radioactive source on the surface of the concrete, and at a height above the surface by raising the detector by means of the vernier screw drive, as was normally done. This test was then repeated by lowering the detector to the surface and then raising the entire gage to the same height as before. There was a difference of several thousand counts between the two readings, indicating that collimation was occurring when the detector was raised by the screw drive. It appears that the aluminum cylinder, acting as a guide for the detector,

absorbs gammas. This collimation effect may be a key to the proper development of the nuclear technique, and studies should be intensified in this area. However, such studies lie outside the scope of this project.

The Microwave Gage

One manufacturer was contacted prior to final instrument selection concerning a portable microwave device which was under development for determination of concrete thickness. This instrument operates on the principle that materials exhibit unique dielectric coefficients, which radically influence the reflection and scattering of microwave signals. Wavelength measurements, therefore, can predict the depth at which a material change occurs; and thus, the depth of concrete can be determined from the different coefficients inherent in the slab and subbase materials.

A demonstration of a prototype of the instrument was witnessed, and the gage did indeed show a promising capability for depth detection with ample sensitivity. However, the prototype had a limit to depth detection of approximately 6 in. According to the developer, this limitation could easily be overcome with higher power microwave signals, and the Federal Communications Commission had been petitioned at that time to grant a license to increase the power.

At the onset of the testing program, the gage had not progressed to the more promising stage, and it was decided to begin the tests without it. It is felt, however, that the system offers excellent potential.

The Radar Gage

During the testing program for Phase I of the project, the researchers were contacted by personnel from the U. S. Army Waterways Experiment Station in Vicksburg, Mississippi, concerning a device developed by the Army to measure pavement and runway layer thicknesses by a swept frequency radar technique. Although the system had proven capabilities, it had been licensed by the FCC at that time to operate only in the Vicksburg, Mississippi, area. Arrangements could not be made, therefore, to bring the apparatus to Harrisburg, Pennsylvania, for operation on the test slabs.

The Field Strength Gage

Several manufacturers were contacted concerning a gage to measure electrical power or field strength at some distance away from a radiating power source. It was felt that such a device would enable development of a relatively simple and inexpensive technique for measurement of pavement thickness. A wire or cable placed on the subbase prior to concrete placement could be attached to a low-power signal generator. Utilizing a simple field strength meter, a measure of the field strength could easily be obtained on the pavement surface directly behind the power source. This value could then readily be translated into pavement thickness.

As none of the manufacturers of field strength meters showed interest in developing the technique, it was not included in the project.

Earth Electrical Potential Method

A natural electrical potential exists between any two points on the surface of the earth. This potential is small, and very sensitive instruments are required to detect it. The method is based upon the theory that a potential difference is caused by changes in the composition of the earth materials. As the roadway section is a portion of the earth's surface, the pavement thickness can be determined by the change in potential.

Two electrodes are placed a given distance apart on the pavement surface. The potential between the electrodes is measured using a null point instrument. The distance between the electrodes represents the depth of the measurement. The potential is plotted against this distance, in inches. Discontinuities, or breaks, in the straight line indicate the location of a change in material. This method is similar to a soils exploration method proposed about 40 years ago.

The method was investigated during the course of the Phase II field studies.

Pulse-Echo Ultrasonic Gage

Near the end of the Phase II field testing program, Nathan L. Smith, Jr., Assistant Chief Engineer in Materials and Research, Maryland State Roads Commission, notified the researchers that Maryland was in the process of developing a pulse-echo ultrasonic gage (PEUG) for measuring pavement thickness. The initial field data indicated that the method appeared promising. The principal investigators on this project visited Maryland and studied the new ultrasonic equipment.

At the time of the first visit, a relationship between the PEUG reading and pavement thickness had been developed for Maryland pavements. The Maryland State Roads Commission then obtained additional field readings, using the calibration curve to estimate pavement thickness. Mr. Smith made all of these data available to the NCHRP 10-8 study.

The PEUG is basically a Branson Instrument Company gage, used for the ultrasonic inspection of steel, with the frequency and power output modified. In operation, power is pulse-supplied to the single piezoelectric crystal; the power input is then stopped, and the crystal is used as a receiver. The time for the ultrasonic wave to travel through the concrete and return to the surface is measured and is indicative of the pavement thickness.

The equipment is simple to operate. The use of the same crystal for both generating the pulse and receiving the echo proved practical. The power input to the transducer was sufficient to identify readily the echo, and the entire equipment operation was stable and reproducible.

This equipment was designed originally to measure the thickness of metal, a material which transmits a constant sound velocity due to its homogeneous, fine-grained structure. Because of the nonhomogeneous structure of concrete, the velocity of the sound pulse is not constant. It may, therefore, be highly desirable to incorporate velocity measurements into the results. The PEUG is shown in operation in Figure B-10.

GENERAL EVALUATIONS

Effect of Environment

Laboratory studies were conducted simulating the extremes in environments which might be encountered in the field. It was not the intent of the project to pursue more intensive studies of the reasons for instrument deviations resulting from these simulated conditions. In the laboratory, the instruments were placed on concrete test slabs, approximately 2 ft square and 6 in. thick in each simulated environment. The tests were carried out according to the manufacturer's instructions, with the results shown in Table B-1. The results of the tests made at $70^{o}F \pm 5^{o}F$ and 40 RH $\pm$ 10 RH (%) were used as a reference when comparing results under other environments. The pachometer was tested under the conditions described above, but on a 6-in.-square by 4-in.-thick concrete block with a No. 3 reinforcing bar placed 2 in. from the surface.

Cost Estimates

Table B-2 compares the approximate cost-per-test for each of the methods. The times for the Ultrasonic-1 and nuclear methods do not include computation of data, which may be several minutes per test. The resistivity method requires much longer computation times, as shown in note (d) of the table.

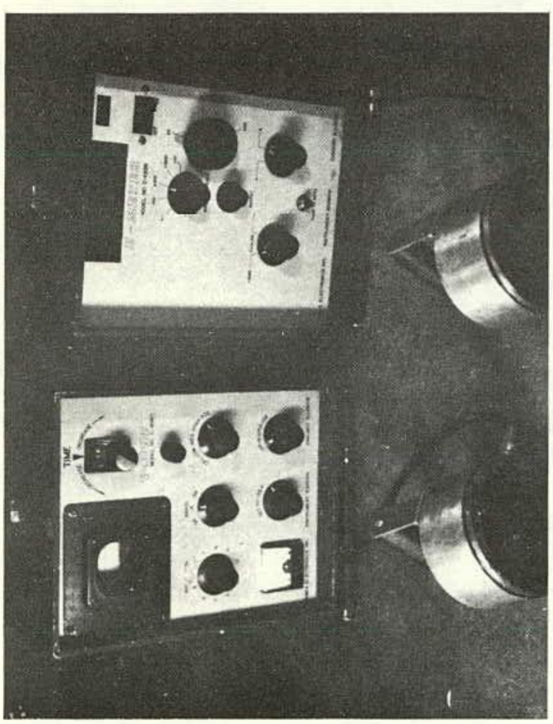

Figure B-1. The Ultrasonic-1 system.

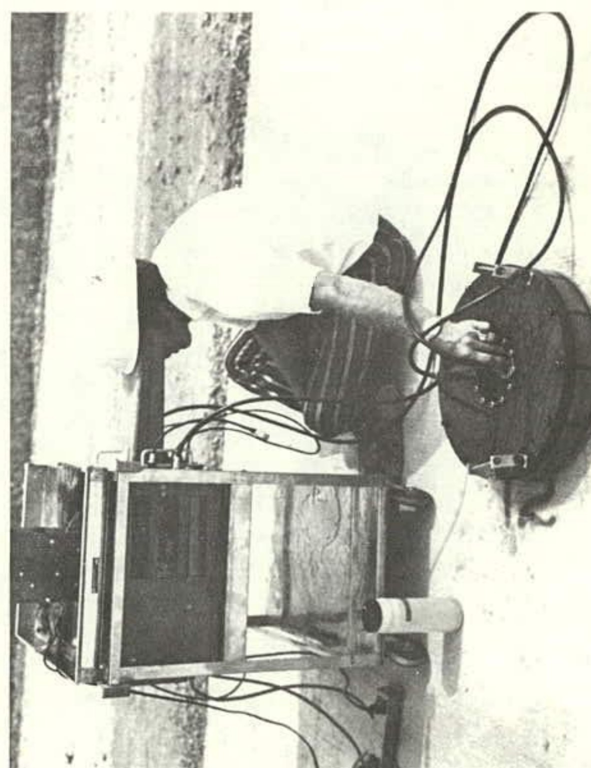

Figure B-2. Thickness determination with the Ohio State ultrasonic gage.

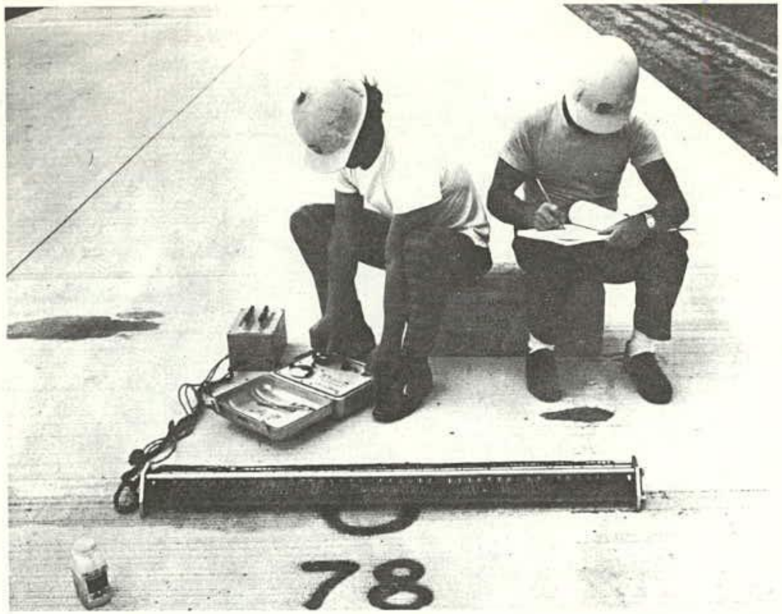

Figure B-5. Modified resistivity gage in operation.

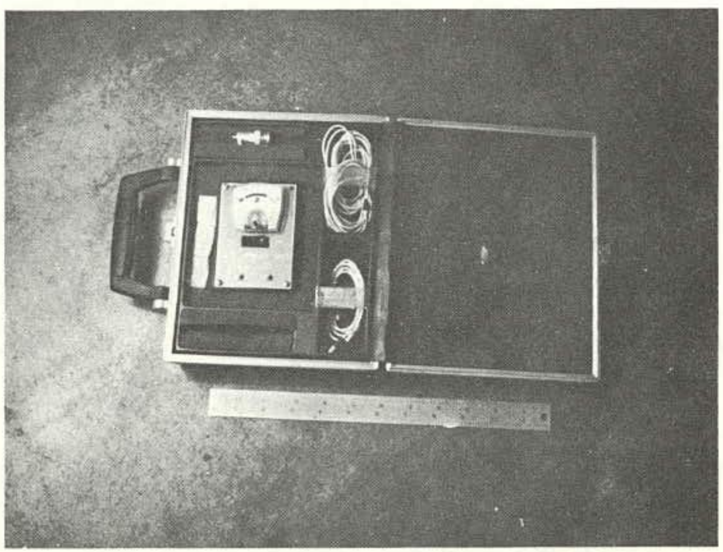

Figure B-6. Miniature crystal force transducer used in the mechanical impact method.

Figure B-3. Pachometer in operation.

Figure B-4. Eddy current proximity gage in operation.

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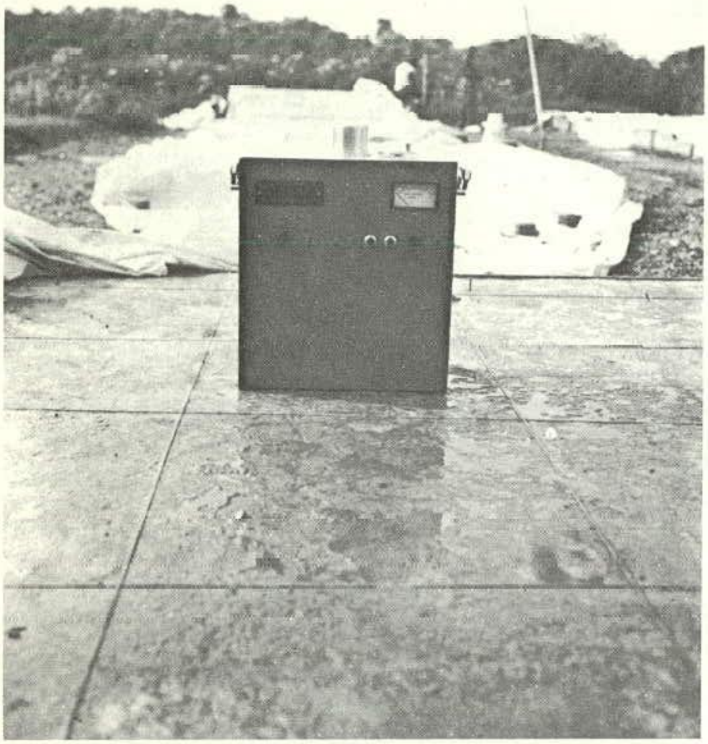

Figure B-8. The nuclear gage.

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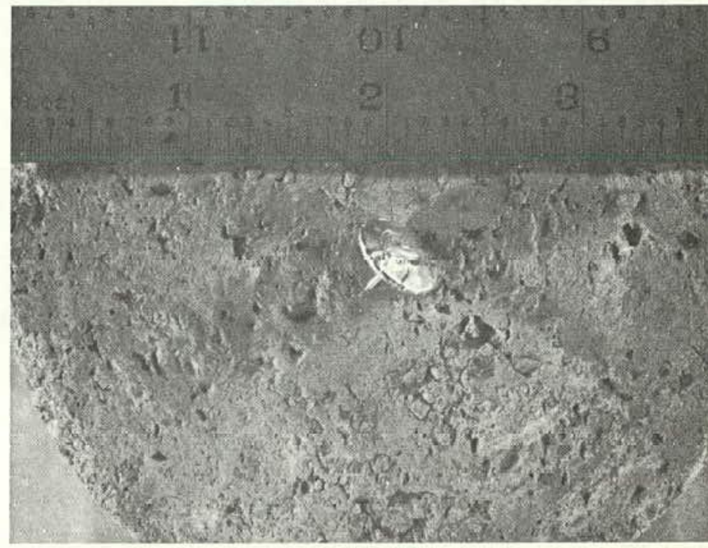

Figure B-9. Typical radiation source used in the nuclear method.

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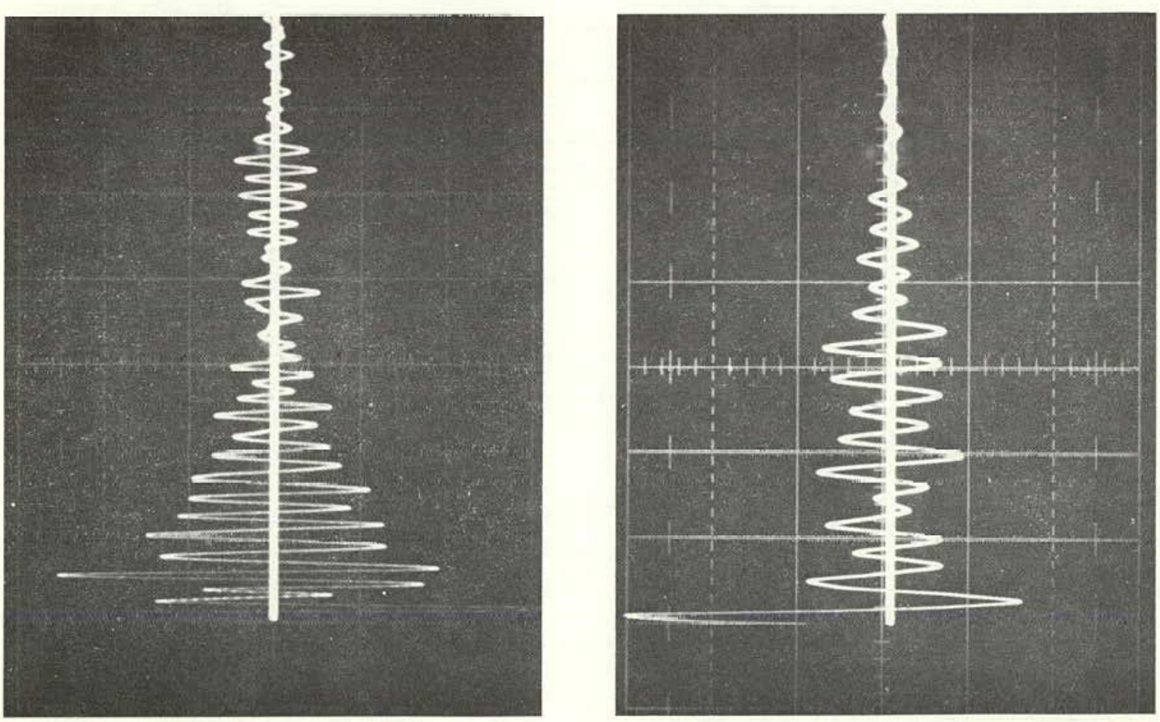

Figure B-7. Typical oscilloscope outputs for the mechanical impact method.

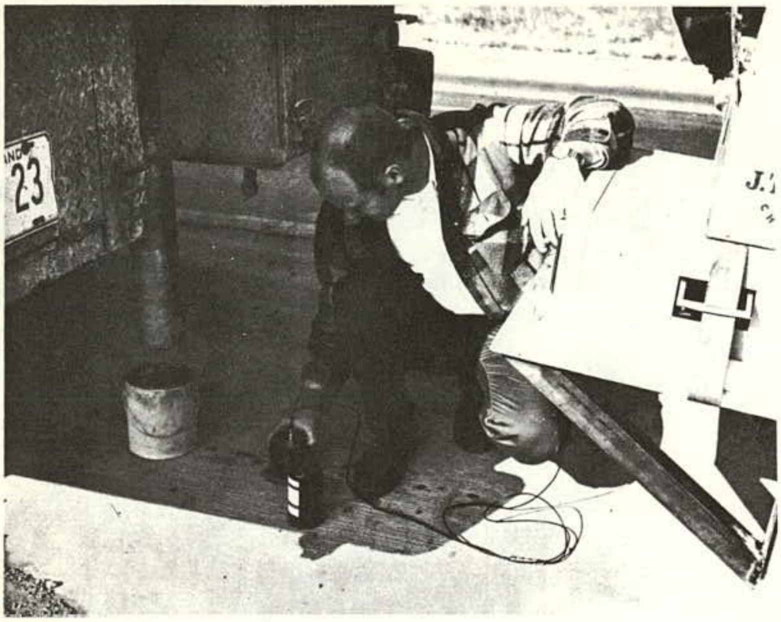

Figure B-10. Pulse-echo ultrasonic gage in operation.

Table B-1. Laboratory Evaluation of Test Methods

METHOD	0°F, 20% RH	70°F, 100% RH	120°F, 5% RH
ULTRASONIC-1	normal	normal	very erratic
OHIO STATE ULTRASONIC	(a)	(a)	(a)
RESISTIVITY (modified)	normal	normal	slowed response
PACHOMETER	normal	normal	normal
EDDY CURRENT PROXIMITY	normal	normal	erratic
NUCLEAR	normal	normal	normal

[a]No laboratory tests (see Ohio State data for laboratory results).

Table B-2. Cost Estimates for the Methods Tested

METHOD	Time per test (minutes)	Number of tests required	Labor costs[a]	Instrument cost per complete test[b]	Total cost per complete test[c]
ULTRASONIC-1	1.0[d]	141	$18.80	$3.33	$22.13
OHIO STATE ULTRASONIC	1.0	26	3.47	0.62	4.09
RESISTIVITY	5.0[d]	29	9.67	1.16	10.83
PACHOMETER	0.5	2	0.07	0.01	0.08
EDDY CURRENT PROXIMITY	0.5	3	0.10	0.01	0.11
NUCLEAR	3.0[d]	63	12.60	2.70	15.30
CORES	(e)	6	--	--	72.00

[a]Labor computed at $4/hr. The two ultrasonic methods required two men. all others required one.

[b]Instrument cost computed on a 3-percent-of-purchase-price-per-month rental basis.

[c]Does not include time spent travelling to individual test sites, or vehicle costs.

[d]Does not include time for computation of data. With computation time, costs per complete test double for the nuclear and Ultrasonic-1 methods, and approximately triple for the resistivity method.

[e]From previous experience, neglecting travel time and expenses, the basic cost of mechanically removing a core is approximately $12.

APPENDIX C

TEST SLAB STUDIES

INTRODUCTION

Results of the literature survey presented in Appendix A indicated that seven major factors could influence concrete thickness measurements, and that six major factors could influence the determination of reinforcement location. Since t o of these factors are the quantities to be measured, there remained eleven factors to be utilized in evaluating the performance of the equipment.

EXPERIMENTAL DESIGN

To evaluate these eleven factors, eight concrete test slabs were placed upon normally constructed bases. The slabs were 10 ft square, separated by at least 5 ft of work area. To eliminate any potential edge effect, the outer 1 ft of the slab was not utilized in the test program. The central 8-ft area was divided into 2-ft squares, each constituting an individual test site. All factors were maintained as constant as practicable within a group of at least four individual test sites, (i.e., a test area) in order to form a subgroup of uniform variables. The variations in the readings between individual test

sites within a test area allowed an estimate to be made of the repeatability. The variations between the readings obtained in the various test areas allowed an analysis of the effect of various factors upon the test results. The test variables, those factors that might influence non-destructive test results, are presented in Tables C-1 and C-2, along with the levels chosen for the experimental design.

The thickness of concrete as determined by the instruments was compared with thickness as determined by levels. This is not to imply that the thickness as determined by levels is correct, but was used in order to have a common base for comparison.

The slabs were designated from A through H, and the individual test sites were numbered from 1 through 16. The test site numbering system and locations at which thickness determination was obtained are shown in Figure C-1. The average thickness of the concrete of a test site was obtained by averaging the four corner thicknesses, and then averaging this value with the center value. Thus, the center value was given four times the weight of a corner value. The reinforcement location was determined by means of cores taken at the completion of the testing program.

CONSTRUCTION OF TEST SLABS

A maintenance yard in Harrisburg with readily available utilities was selected as the location for constructing the test slabs. At no cost to this project, PennDOT maintenance forces prepared an area 40 ft

wide by 70 ft long, consisting of an 1-1/2-foot depth of compacted select material.

On one half of the prepared area, 6 in. of 1-1/2-in. maximum size limestone subbase was placed and compacted. Slabs A. C, D, and E were placed on this material. On one fourth the area, 2½-in. maximum size limestone subbase was placed and compacted. Slabs B and F were placed on this material. The remaining two sections of the area received subbase material of 1-1/2 sack plant-mixed cement-treated limestone, and slag, respectively. Slab G was placed on the cement-treated limestone, and Slab H was placed on the slag subbase.

The thicknesses of the subbase, as determined by differential levels, are listed in Table C-3. The wet densities of the compacted subbase, as determined by nuclear gages, are shown in Table C-4. The condition of the subbase is shown in Figures C-2 and C-3.

Wooden forms were placed on the subbase for each slab. The test sites were referenced by means of string lines placed across the forms. After the reinforcement was positioned and the asphalt membranes placed, levels were taken on the subbase surface.

Each test slab was cast individually. The concrete was placed in two lifts, each vibrated with a small electric vibrator. To avoid segregation, concrete was placed in each quarter of the area of the test slab and moved by shovel. To assure as uniform a mix as possible, all of the concrete in a slab was from one transit mix truck load.

Ten concrete cylinders, 6 by 12 in., were taken for each test slab, during placing. The cylinders were stored at the test site and broken at various times. The slump and air content of the mix were determined while the concrete was being placed. Typical cylinder strength and the average values for air content and slump are shown in Table C-5.

The contractor struck off the top of the slab and hand troweled the surface. Where a rough surface was desired, a broom was dragged across the wet concrete. As soon as the contractor had completed placement, testing was begun. A moveable bridge permitted testing of the fresh concrete. Initial data were generally completed for a slab on the day of concrete placement. The second day after placement of concrete, another set of readings was usually obtained for each instrument. These first two sets of data constituted the early readings, and were for the purpose of determining the usefulness of the gages immediately after placement of the concrete. Two further sets of readings were obtained for each instrument at one week and several weeks after placement of the concrete. These readings were to determine the usefulness of the equipment on hardened concrete.

These four sets of readings constituted the normal testing pattern. In most cases, all testing with a gage was performed by the same operator. Occasionally, because of problems such as equipment failure and weather, retesting was necessary to complete the full data pattern. Retesting was done as soon as possible, and the time spent in this effort represented less than 5 percent of the total. As later analysis indicated that all four sets of readings were statistically the same, it was not felt that this procedure introduced error into any set of readings.

DATA ANALYSIS

Because of the large number of variables involved, the experiment was developed along the lines of a "partial factorial" design. This approach permitted evaluation of main effects from the extraneous or design variables, but did not permit evaluation of many intetactions. To have allowed for evaluation of all possible interactions (i.e., a complete factorial design) would have required time and facilities far beyond the allotted capacity of this project. It should be pointed out that this situation necessitated considerable forethought and planning to assure that all the important main effects and interactions were included. These main effects and interactions of the design variables were evaluated by analysis of variance. Comparison of the test variables with "standard" values was achieved by means of common statistical tests suited to this purpose (primarily Student's t-test, but occasionally the less sophisticated, but non-parametric Sign test).

Whenever possible, the test variable for a given instrument was determined as a mean value of several readings over a test area. A test area is a group of four 2-by-2-ft test sites, as described previously, in which the design variables related to a given test variable are at a constant level. A listing of the test sites that make up each test area, for each of the two groups of design variables previously listed, is given on Table C-6. Because of very special conditions, it was not possible to do this with the eddy current proximity gage (for slab thickness). In these measurements individual test sites were used, as shown in Figure C-4.

Slab Thickness Measurements

General.--Five instruments, and coring, were compared with differential level readings (the assumed "standard" thickness values). The instruments involved were:

1. Nuclear gage (measurement of gamma radiation from buried source)
2. Resistivity gage
3. Two types of ultrasonic gages
4. An eddy current proximity gage.

These instruments are described in detail in Appendix B.

Means and standard deviations for all test areas, measured by all the methods, are summarized in Table C-7.

Differential Levels.--Elevations, to the nearest 0.001 ft, were determined at the corners and centers of each of the 128 2-by-2-ft test sites before and after slab placement. The differences in elevations before and after, or differential levels, were considered to be the official slab thicknesses at the various points. The representative thickness of each test site was expressed as the weighted average of the differential level readings, where the thicknesses at the corners were each weighted one-fourth and the center reading was given full weight. Test site thickness is tabulated in Table C-8.

Core Measurements.--Cores were obtained for measurement from each of the locations where differential levels were taken, as well as from other locations for special purposes (depth of reinforcement and slab thickness at measurement locations of the eddy current proximity gage). To determine pavement thicknesses, the cores were placed top down, and probes were used to measure to the bottom surface. The probe had a 1/8-in. radius spherical tip, and measurements were made at five points approximately 72 degrees apart, 1 in. from the edge of the core. A single measure of each core was obtained from the simple arithmetic mean of the five readings. Table C-9 compares the difference between core length determinations and the differential level readings. A simple non-parametric statistical test, the Sign test, was employed (see bottom of Table C-9) to show that no significant difference exists at the 95 percent level between slab thickness measurements by differential levels and measurements of cores taken from the slab.

The Nuclear Method.--The nuclear method was discussed in detail in Appendix B. Some preliminary studies were carried out to evaluate techniques in using the equipment and interpreting the data. The radiation source employed in this experiment emitted gamma radiation at two energy levels. Since the two gammas are absorbed at different rates by the attenuating medium (the concrete slab), the thickness of the slab should be a function of the ratio of the two emergent gammas. However, comparison of the gamma ratio with the thickness of the slab at 56 test sites failed to give a significant correlation at the 95 percent level. The results are shown in Table C-10.

A second special test involving the nuclear method was concerned with the use of the ratemeter versus counter readings for determination of slab thickness. Comparisons of slab thicknesses at 24 test sites from differential levels (standard) with thicknesses using the ratemeter and the counter are shown on Table C-11. Using the Sign test, it is shown that both give results that are not significantly different (at the 95 percent level) from the differential level thickness determinations (see bottom of Table C-11). However, the mean deviation is somewhat greater for the ratemeter than for the counter (+0.46 versus -0.27 in.). The counter was used for the remaining tests using the nuclear method, primarily because of its simplicity.

The analyses of variance, to examine the contributions of the various slab design factors to variance in the nuclear method of measuring slab thickness, revealed that the following factors had significant effects at the 95 percent level or greater (see Table C-12):

1. Bottom condition
2. Presence of asphalt membrane
3. Base type.

Thickness measurements by the nuclear method, made as soon as the concrete was rigid enough to support the instrument, were compared with later readings, revealing no significant difference at the 95 percent level. The comparisons were made by means of the Student's t-test and the results are shown on Table C-13. This means that the instrument is as suitable for use on fresh concrete as on mature concrete. (The single significant result from 26 areas is within the expectations of the 95 percent significance level.)

Table C-13 also shows that slab thickness measurements by the nuclear method are not significantly different from thicknesses determined by differential levels (21 of 26 test areas show no significant difference). However, it should be pointed out that the mean standard deviation for the nuclear method is very high (1.205 in., see Table C-14), which in part accounts for the fact that significant differences generally could not be detected by the t-test. It is because of the great variability of this method that it is not recommended.

Several special tests were conducted using the nuclear gage in an attempt to determine why much of the data did not appear to follow the relationship of count diminishing as a function of distance squared. Several energy spectrum tests were performed and agreed with the information supplied by the manufacturer, indicating that the gage was performing properly.

Test results from the field indicated that the three tests at different heights taken at each test site did not follow an inverse square law relationship at more than half the test sites used in the study. The four tests on a given site taken at different times during the testing program indicated that data for a particular test site were repeatable during the testing program. Thus, although data taken at a given site did not in itself follow an accepted relationship, the data were repeatable at widely separate time intervals, again indicating that the gage itself appeared to operate satisfactorily.

At the start of the project the nuclear gage performance was checked on a 6-in. slab. The results appeared satisfactory and were reproducible. When the difficulty previously mentioned was noted the gage

was returned to the laboratory and again checked on an 8.1-in.-thick slab. Ten repeat readings were obtained with the detector at 0, 2, 4, 7, and 9 in. above the slab surface. The results are shown in Figure C-5. The zero-in. readings were consistently low, and the 2-in. readings were consistently high. The ranges of the 10 readings, also shown in Figure C-5, are not outside acceptable limits. The indicated thickness, about 16-1/2 in., is twice the actual thickness. If the 2- and 7-in. readings only are used, the indicated thickness is nearer 8 in. This consistent error appeared on a majority of the test sites with the nuclear gage.

A series of special tests were conducted with the nuclear gage in the field in an attempt to explain the above noted difficulty. The first special test involved running a radiation profile across two adjoining test sites with the detector on the slab surface, then at heights above the slab of one-half the slab nominal thickness and of the slab nominal thickness. Next, cross-sections to the profiles at each test site were obtained. Typical results of these determinations are shown in Figures C-6 and C-7. The radioactive sources generally were very close to the center of the test site and did not appear to have moved during the placement of the concrete. This was later confirmed during the coring operations. The tendency for the readings to differ from the inverse square relationship is also evident in Figures C-6 and C-7.

The second special test was performed to evaluate the one-fourth count procedure, which is based on the inverse squares law. In this procedure it is assumed that the count obtained with the detector height equal to the slab thickness is one-fourth of the count at the

surface. These tests were performed by obtaining a set of data on one test site, then moving to another test site and obtaining a set of data, then returning to the original test site for another set of data and so on. Typical data are shown in Figure C-8. As may be seen by the spread of the individual test data, consistent readings are obtained at any given detector height above the pavement surface. As a slight shifting of the points may result in a significant change in indicated thickness, this type of data is difficult to analyze. Slab A, Test Site 7 in Figure C-8 indicates that a range from 4.7 to 6.3 in. could be obtained depending upon the points used.

A comparison was made between the indicated thicknesses from the special test results using five points and the regular results using three points. This comparison is shown in Table C-15. There was no improvement in the indicated thickness using five points when compared to the three-point data.

A third special test was carried out to evaluate the reproducibility of the nuclear gage. Two test sites were used on each of three test slabs. Readings were taken alternately on the two sites for each slab at three different positions: (1) at the surface, (2) at a height equal to one-half the nominal slab thickness, and (3) at a height equal to the nominal slab thickness. Ten replicate readings were obtained for each site. The data are tabulated in Table C-16.

It can be seen that the coefficients of variation, tabulated in the last row at the bottom of each column in Table C-16, are generally quite low, indicative of good reproducibility. Walker (128) indicates that a coefficient of variation equal to or less than 12 percent shows

excellent control. A more quantitative indication of the degree of reproducibility may be appreciated from the fact that with 10 replications (as was the case here) the true mean lies within ± 5 percent of the sample mean at least 95 percent of the time when the coefficient of variation is 7 percent or less, and within ± 10 percent of the sample mean at least 95 percent of the time when the coefficient of variation is 14 percent or less. Only one set of readings appears to be excessively variable--that from the 12-in. readings of Slab E, Site 4. This one set also has a very low mean value, indicating that perhaps the background radiation may have contributed to the problem here.

These data reveal only the variability of replicate readings at given locations and elevations of the detector. The computed pavement thickness values display considerably greater variability.

Limited testing was done to check a possible collimation of the sodium iodide detector in the gage. The detector moves vertically in an aluminum tube, and it was thought that counts of particular energy gammas might be influenced by scattering or absorption due to collimation by the aluminum tube. Tests were, therefore, conducted over a nuclear source with the detector raised to 6 in. by means of the vernier adjustment screw as was done in normal testing procedure. Then, the test was repeated but leaving the detector to the zero or surface position and raising the entire gage 6 in. Table C-17 indicates that there was a definite collimation effect inherent in the gage; but since the count with the entire gage raised was higher than that with the detector raised, the results of tests would indicate much greater thicknesses than were determined by the normal testing procedure. A more thorough investigation of this effect was outside the scope of the project.

The Resistivity Method.--The resistivity method was discussed in detail in Appendix B. It should be noted that the resistivity method provides measures of depths to reinforcement and bottom of base course as well as slab thickness. Only slab thickness measurements will be discussed in this section. Measurement of depth to reinforcement will be covered in the next section.

The analyses of variance, to examine the contributions of the various slab design factors to variance in the resistivity method of measuring slab thickness, revealed that the following had significant effects at the 95 percent level or greater (see Table C-12):

1. Strength of the concrete
2. Bottom condition
3. Base type.

Thickness measurements by the resistivity method, taken as soon as the concrete was rigid enough to support the instrument, when compared with later readings, revealed that no significant difference existed at the 95 percent level. The results are shown on Table C-13. As in the case of the nuclear method, only one test out of 26 showed a significant difference. Therefore, the resistivity method, like the nuclear method, is as suitable for use on fresh concrete as on mature concrete.

Table C-13 also reveals that slab thickness measurements by the resistivity method are significantly different from the thicknesses determined by differential levels in 8 of the 26 test areas. This

appears to be somewhat poorer than the results from the nuclear method, but the mean standard deviation for the resistivity method is considerably lower than for the nuclear method (0.812 versus 1.205 in., see Table C-14), which increases the sensitivity of the t-test. A better indicator of the relative merits of the two methods is a comparison of their respective mean differences with the differential level determinations which are 0.06 and 0.23 in., respectively, for the resistivity and nuclear methods (see Table C-18).

Two special tests were carried out with the resistivity equipment. The first involved the taking of three repeat readings on each of nine test sites. The purpose of this test was to determine the inherent variability of the equipment, or repeatability without regard to actual values of slab thickness or reinforcement depth. The results are summarized in Table C-19. The mean coefficient of variation for the thickness measurements shown on Table C-19 is 4.4 percent and for reinforcement depth is 7.3 percent. In accordance with the previous discussion, these figures indicate excellent reproducibility.

The second test involved the taking of four readings per site, consisting of readings along the diagonals and bisectors of the sides. The purpose of this test was to determine the variability of the instrument within a test site. Obviously, this consists of a combination of the inherent variabilities of the equipment and the slabs. The results of this test are summarized in Table C-20. The mean coefficients of variation in this case were 7.0 percent and 11.3 percent for the slab thickness and reinforcement depth, respectively. Since variances are additive and the coefficient of variation is proportional to the square

root of variance, the inherent variability of the slab parameters (expressed as coefficient of variation) can be computed as follows:

Thickness: $\sqrt{(7.0)^2 - (4.4)^2} = 5.4\%$

Depth of Reinforcement: $\sqrt{(11.3)^2 - (7.3)^2} = 8.6\%$

Reference to Table C-14 reveals that the standard deviations for slab thickness by differential leveling and reinforcement depth by coring are 0.3465 in. and 0.2378 in., respectively. If it is assumed that the overall average slab thickness is about 9 in. and reinforcement depth about 3 in., approximate values of coefficient of variation representing inherent slab variability can be computed to compare with the results shown above. These turn out to be 3.9 percent and 7.9 percent, respectively, which, in view of their approximate nature, provides a good check on the results of the special tests.

These tests indicate, then, that the inherent variability of the resistivity method is no greater than (and perhaps a little less than) that of the measured parameters themselves (i.e., the slabs).

The Ultrasonic Methods.--Two devices which utilize the ultrasonic wave propagation technique for thickness determination were evaluated. The first, Ultrasonic-1, uses piezo-electric transducers of the same size for both the transmitter and the receiver. The second, the Ohio State ultrasonic gage employs a large doughnut-shaped transmitting transducer and a smaller circular receiving transducer. The details of the two types of equipment are discussed in Appendix B.

The analyses of variance, to examine the contributions of the various slab design factors to overall variance in the Ultrasonic-1

method of measuring slab thickness, revealed that the following had effects that were significant at the 95 percent level or greater (see Table C-12):

1. Strength of the concrete
2. Slab thickness
3. Bottom condition
4. Base type.

Analyses of variance were not performed with the Ohio State ultrasonic gage because of insufficient data. However, the same factors affecting the Ultrasonic-1 measurements should be significant here, too. This contention is supported in at least one instance by the fact that it was not possible to obtain readings with the Ohio State gage on Slab II (the slab on smooth slag base) which indicates that base type significantly affects ultrasonic measurements.

Thickness measurement by the Ultrasonic-1 method, made as soon as the concrete was rigid enough to support the instrument, when compared with later readings, revealed that significant differences existed at the 95 percent level for 9 of the 26 test areas (see Table C-13). No data were obtained on fresh concrete with the Ohio State gage, but there is no reason to suspect that the two methods should differ in this respect. It appears that the ultrasonic methods are, at best, suspect for use on "fresh" concrete.

Table C-13 also reveals that slab thickness measurements by both ultrasonic methods are significantly different from the thickness determined by differential levels (in 14 of 26 test areas for Ultrasonic-1, and 10 of 26 test areas for the Ohio State gage). However, the standard

C-17

deviation and the mean deviation from the differential level reading for the Ohio State gage are small (0.768 and 0.12 in., respectively, see Tables C-14 and C-18), indicating good potential for this method. The Ultrasonic-1 method, on the other hand, is highly erratic, as indicated by mean standard deviation and mean deviation from differential levels of 1.800 and 2.43 in., respectively (see Tables C-14 and C-18).

A series of special tests were carried out to evaluate the reproducibility of the Ultrasonic-1 gage and to determine the factors that influence the results obtained with this instrument. Five to 12 replicate thickness determinations were made on 8 test sites on different days, at different times of day, and by different operators. A summary of the results appears in Table C-21.

With regard to reproducibility, the coefficient of variation ranged from 3.4 to 25.3 percent, as shown in Table C-21 with about half of the results above and half below 10 percent. This would indicate that the Ultrasonic-1 method is internally reproducible to an acceptable degree in only about half the cases. Therefore, it can only be stated that the results are inconclusive with respect to reproducibility. Likewise, Student's t-tests on the data for effect of time of day and operator effects gave inconclusive results as shown in Tables C-22 and C-23, where in each instance half of the results were positive and half negative. The inconsistency of the Ultrasonic-1 method for obtaining thickness measurements shown here supports the observations of Scholer (127). Not only is the variability high but, more importantly, this device fails to even correlate significantly with slab thickness.

C-18

The Eddy Current Proximity Method.--A description of the eddy current proximity gage is given in Appendix B. This technique was evaluated in terms of determining depth of mesh-type reinforcement as well as slab thickness. Only its use in slab thickness measurement will be covered in this section. Use of the instrument for measurement of mesh depth will be discussed in the next section of this Appendix.

For slab thickness measurements by this method, it is necessary that a metal plate or foil be placed at the base of the slab. Aluminum foil was placed under four test sites each in Slabs E and H, and 12-by 12-in. aluminum plates were placed in a total of eight locations under the peripheral areas of Slabs A and C. Because the possibility existed that the presence of the aluminum would adversely affect readings with the other instruments, an analysis was carried out on Slabs E and H, comparing readings on test areas underlain with aluminum with those on test areas not having the aluminum. This was done for the nuclear, resistivity, and both ultrasonic methods. Whenever sufficient data existed to carry out the analysis (using the Student's t-test), no significant difference was found at the 95 percent level between the two conditions, indicating that the aluminum had no effect. The results of this study are detailed in Table C-24.

An insufficient number of test sites was available to permit an analysis of variance to examine the contributions of the various design factors to the overall variance by this method. The eddy current proximity

C-19

gage was not used on "fresh" concrete and so no comment can be made regarding its suitability for early thickness determinations. However, in theory, the age of the concrete should have no effect.

In comparing slab thickness measurements by the eddy current proximity gage with "standard" values, core lengths were used rather than differential levels for the "standard" thicknesses. This was necessitated by the fact that eight of the test sites were in areas not covered by differential level readings. Cores, however, were extracted at those locations. The comparison of the readings is made in Table C-25. It is readily evident from this table that the eddy current proximity gage compares favorably with core measurements (at the 95 percent significance level) for the thin (6-in.) slab, but not for the thicker ones. However, the fact that the mean standard deviation for this instrument is very low (0.248 in.--the smallest value obtained for all instruments tested, see Table C-14) indicates that this instrument shows considerable promise with, possibly, use of other calibration factors for slabs thicker than 6 in.

Depth and Spacing of Reinforcing Steel

General.--One instrument was evaluated for determining the depth and spacing of reinforcing bars and depth of mesh (pachometer), one for determining depth only of bars and mesh (resistivity gage), and one for depth of mesh only (eddy current proximity gage). "Standard" values for purposes of comparison were obtained from steel locations in the cores.

C-20

The Pachometer Method.--The analyses of variance, to examine the contributions of the various slab design factors to overall variance in the use of the pachometer for bar depth measurements, revealed that the following factors were significant at the 95 percent level or greater (see Table C-12).

1. Surface condition
2. Bar size
3. Bar depth
4. Bar spacing
5. Number of layers of bars.

The interaction between bar size and surface condition was also found to be significant. While there would appear to be severe limitations on the use of the pachometer, in actuality the small mean standard deviation for bar depths with this instrument (0.159 in., see Table C-14) indicates that, with proper calibration, the instrument holds promise. Table C-26 does reveal that there is a significant difference (at the 95 percent level) between bar depths as measured with the pachometer and results from cores. But, as shown on Table C-18, the mean difference is a rather constant function of depth, indicating again that proper calibration would permit the use of this instrument for measuring bar depths. It should be noted at this point, however, that the pachometer measures to the top of the bars, while the core measurements were made to the center of the bars. Also, the pachometer is not capable of detecting the lower layer of two layers of reinforcing steel, only the depth to the top layer can be determined by this method.

When bar depth readings made with the pachometer as soon as the concrete was rigid enough to support the instrument were compared with later readings at the same locations, no significant difference was found to exist at the 95 percent level for 15 of 16 test areas (see Table C-27).

The pachometer was shown to be capable of determining horizontal positions, or spacing, of reinforcing bars with excellent accuracy. Figure C-9 shows the manner in which bar spacings were compared, and Table C-28 details the results. In only 2 test areas of a total of 52 was there a significant difference at the 95 percent level between bar spacings as determined with the pachometer and those obtained from measurement of core holes. Further, the mean difference between pachometer and core hole results was only 0.054 in.

In measurement of depth of mesh-type reinforcement with the pachometer, the results were found to be significantly different (at the 95 percent level) from the depths measured from cores (see Table C-29), and the mean difference increases with depth. These observations coincide with those related to the use of the pachometer for depth of reinforcing bars. Also, the mean standard deviation for mesh is quite low (0.337 in., see Table C-14), as was also the case for bars. Therefore, the conclusion reached previously--that with proper calibration, the instrument shows promise--holds true for measurement of depth of mesh as well. As in the case of bars, however, the pachometer will not "see" the lower of two layers of mesh.

A special test was carried out on the pachometer to assess the effect of operator variability on bar and mesh depth and bar spacing determinations. Three operators were used. Each measured a set of designated test sites once (no replication). An analysis of variance of the resulting measurements (Table C-30) revealed that the operator is not a significant source of variability (at the 95 percent level) for bar depth and spacing, but is a significant source of variability in measurement of mesh depth.

The Resistivity Method.--As mentioned previously, the resistivity method provides a measure of bar and mesh depths as well as thickness of slabs. A major advantage for the resistivity method is that the data for slab thickness and depth of reinforcement are obtained simultaneously. Furthermore, unlike the pachometer, it is capable of "seeing" multiple layers of bars or mesh. Comparison of bar depths from resistivity measurements with core determinations by means of the Student's t-test revealed significant differences at the 95 percent level in only 3 of 20 test areas (see Table C-26). Also, while the mean standard deviation is somewhat higher than for the pachometer for bar depth measurements (see Table C-14), the mean difference between resistivity measurements and core readings is much lower (see Table C-18).

Comparison of mesh depths from resistivity measurements with core determinations by means of the Student's t-test gave mixed results (see Table C-29). On the thin slab (Slab B) the results were significantly different at the 95 percent level, while on the thicker slab (Slab D) they were not, even for the depth of the lower of two layers of mesh.

The overall mean difference between resistivity and core measurements for mesh depth was 0.68 in. (Table C-18).

Eddy Current Proximity Method.--It was discovered by accident that the eddy current proximity gage "sees" mesh, but not bars. Comparison of depths of mesh measured by this instrument with depths from cores showed significant differences at the 95 percent level in all test areas (see Table C-29). However, the mean difference between eddy current proximity gage and core measurements was quite constant, though large (averaging 1.25 in., see Table C-18). Since the mean standard deviation of these measurements was only 0.294 in. (see Table C-14), however, it appears that with the application of suitable correction factors this instrument might be useful for measuring depth of mesh. It should be noted that the eddy current proximity gage shares the drawback of the pachometer in being unable to detect the presence of lower layers of mesh where more than one layer exists.

Correction of Instrument Readings

Linear regression analyses were performed for each data set of instrument readings versus "standard" values to provide, for each instrument, a correction equation of the form:

Measured value = (a factor) x (instrument reading) + (a constant)

The results of the regression analyses are presented in Table C-31.

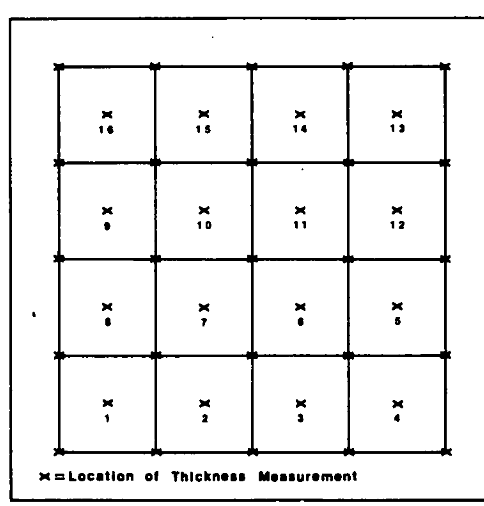

Figure C-1. Test site numbering system.

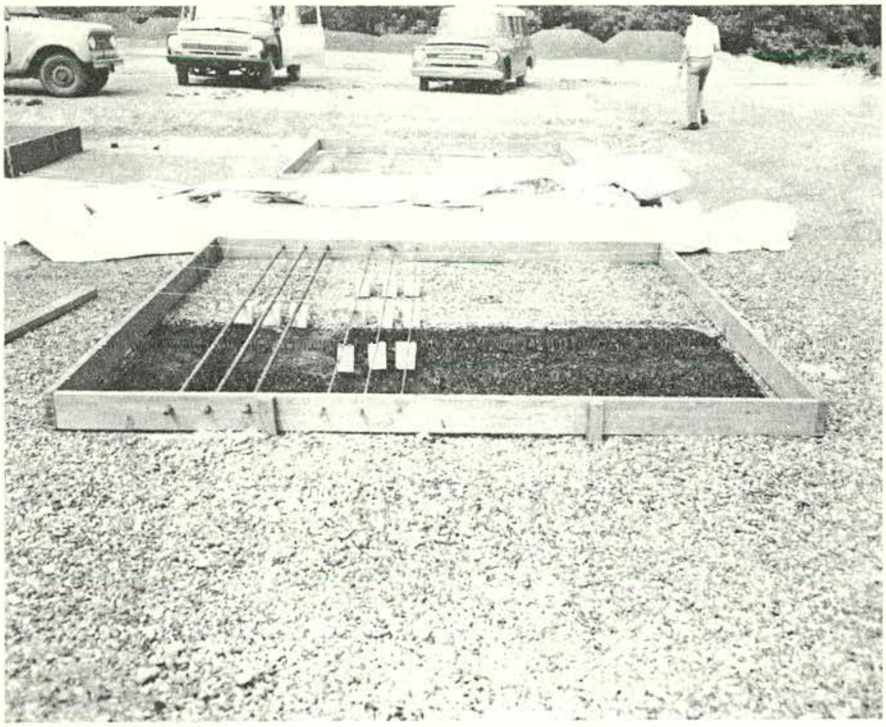

Figure C-2. Test Slab A, showing subbase texture, reinforcement and asphalt membrane.

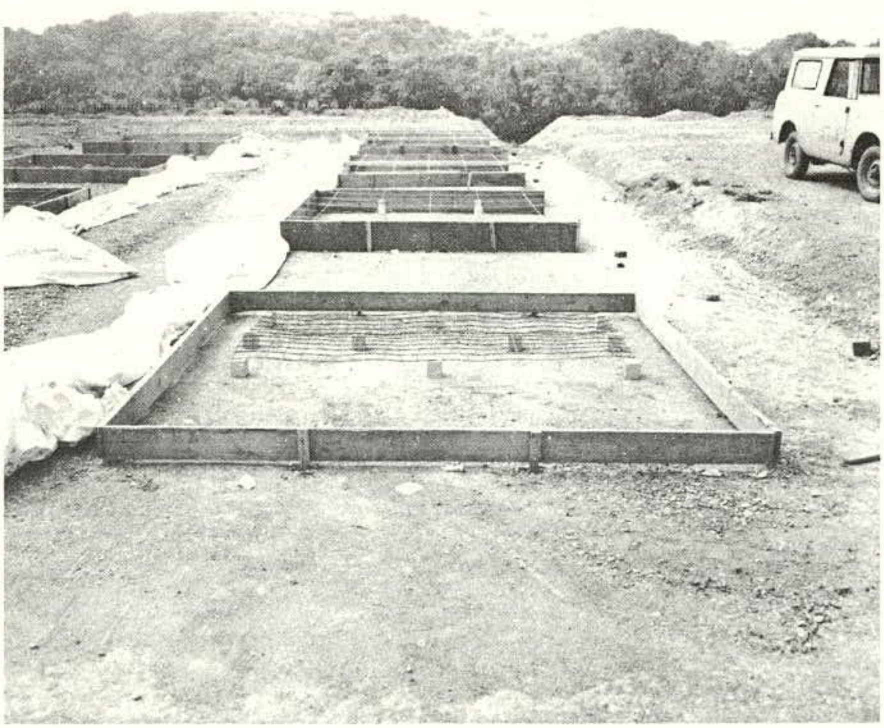

Figure C-3. Test Slab B in foreground, showing smooth subbase texture and wire fabric.

C-26

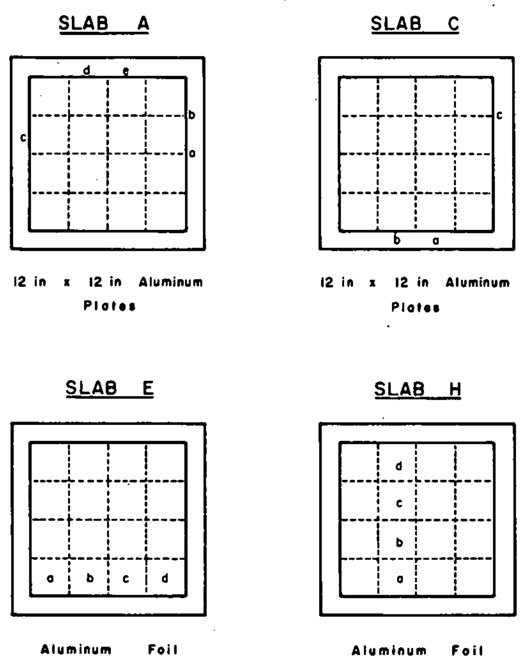

Figure C-4. Eddy current proximity gage test locations.

C-27

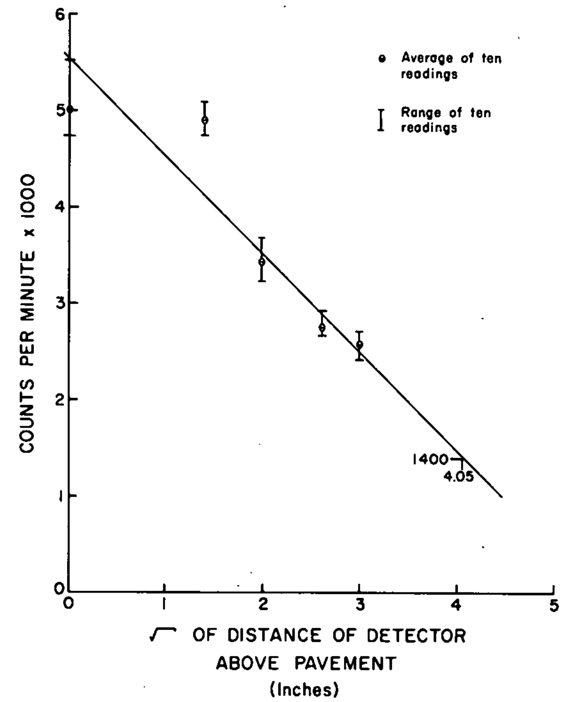

Figure C-5. Nuclear gage test results on an 8.1-inch slab in the laboratory.

C-28

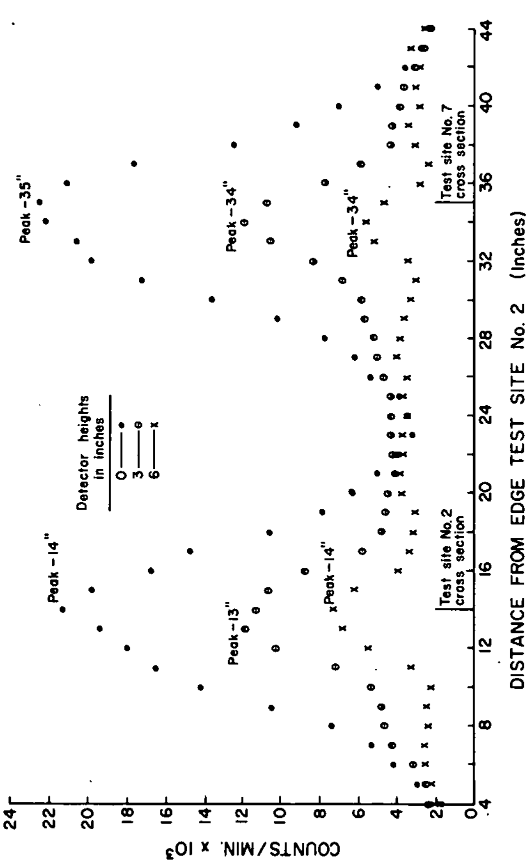

Figure C-6. Profile of radiation for Slab A, Test Sites 2 to 7.

C-29

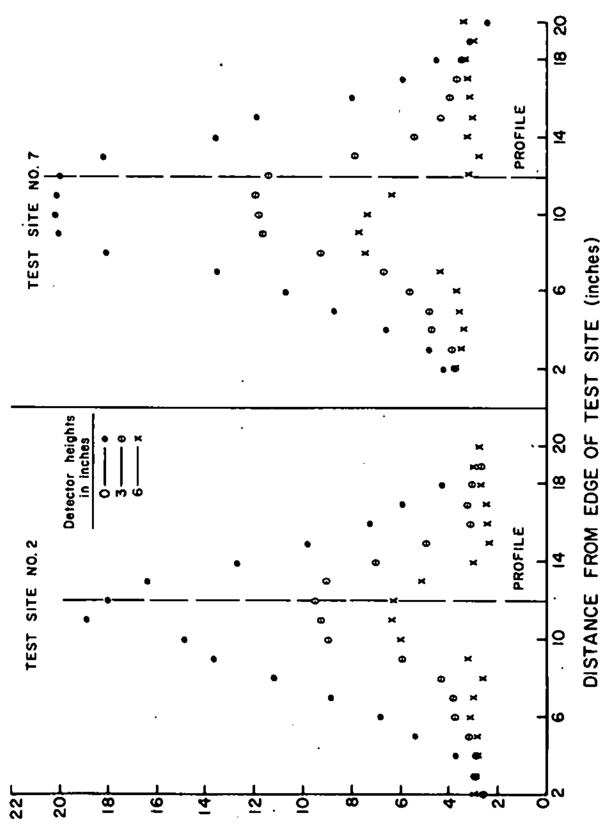

Figure C-7. Radiation cross-sections for Slab A, Test Sites 2 and 7.

C-30

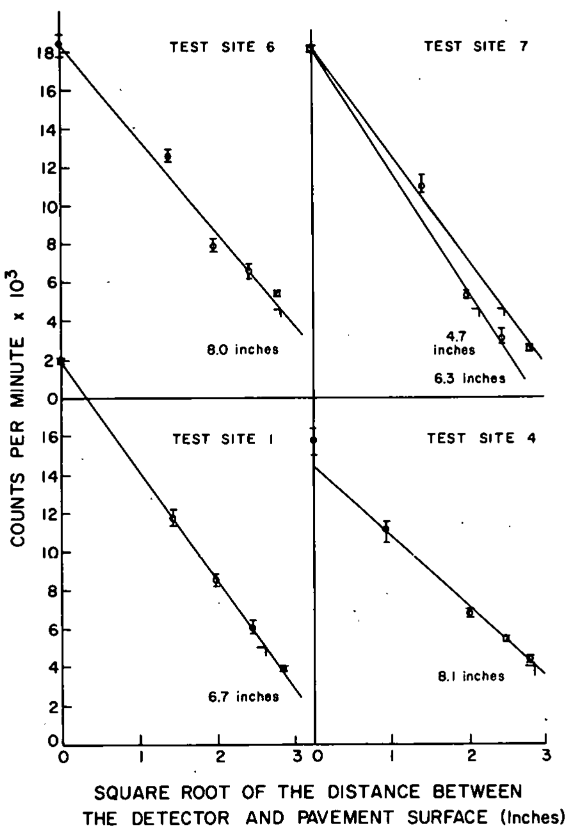

Figure C-8. Repeat nuclear test on Slab A.

C-31

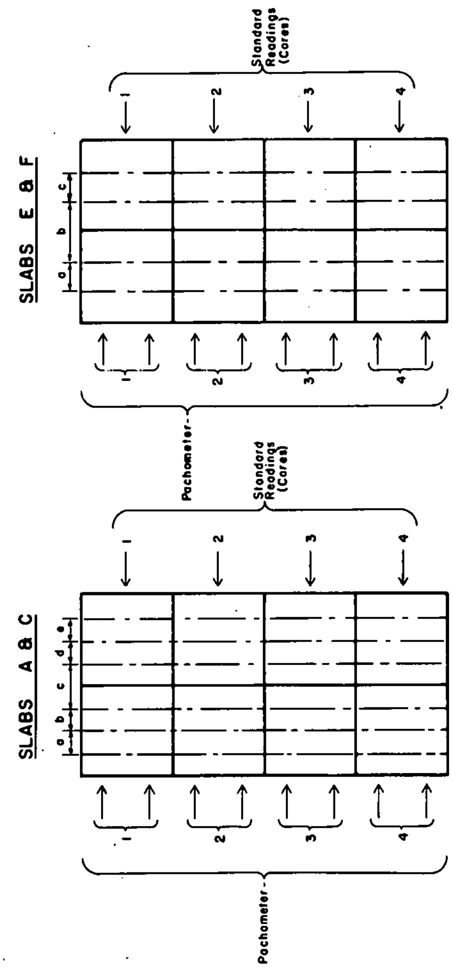

Figure C-9. Comparison of standard (core hole) measurements with pachometer readings for spacing of reinforcing bars.

C-32

Table C-1. Factors Considered in Measurement of Concrete Thickness

Slab:	A	B	C	D	E	F	G	H
Surface Condition								
Smooth	X		X		X			
Rough		X	X	X	X	X	X	X
Strength								
High	X	X	X			X	X	X
Low				X	X			
Thickness								
6 in.	X	X						
9 in.			X	X			X	X
12 in.					X	X	X	X
Reinforcement								
Reinforced	X	X	X	X	X	X		
Plain	X	X	X	X	X	X	X	X
Bottom Condition								
Rough	X		X	X	X			X
Smooth		X				X	X	
Membrane								
Yes	X					X	X	
No	X	X	X	X	X	X	X	X
Base Material								
Normal	X	X	X	X	X	X		
Slag								X
Cement Treated							X	

C-33

Table C-2. Factors considered in determination of reinforcement location.

SLAB:	A	B	C	D	E	F	G	H
Depth Reinforcement							none	none
2 inches	X	X				X		
4 inches			C	C				
6 inches					X			
Type Reinforcement								
Bars	X		X		X	X		
Fabric		X		X				
Spacing, Bars								
6 inches	X		X					
8 inches					X	X		
Fabric Opening								
4 inches		X						
6 inches		X		X				
Size Bars								
No. 3	X		X		X	X		
No. 6	X				X			
Number Layers								
One	X	X	X	X	X	X		
Two			X	X		X		

Table C-3. Thickness of Subbase, as Determined by Differential Levels

LOCATION	THICKNESS OF SUBBASE IN FEET							
	Slab A	Slab B	Slab C	Slab D	Slab E	Slab F	Slab G	Slab H
Center	0.67	0.49	0.61	0.52	0.37	0.41	0.45	0.45
N-W Corner	0.72	0.64	0.58	0.49	0.40	0.45	0.55	0.49
S-W Corner	0.52	0.57	0.59	0.47	0.53	0.41	0.53	0.67
S-E Corner	0.58	0.43	0.64	0.54	0.48	0.33	0.46	0.51
N-E Corner	0.84	0.53	0.55	0.52	0.39	0.36	0.54	0.43

Table C-4. Wet Densities of the Compacted Subbase, as Determined by Nuclear Gages

Test Site No.	Wet Density in Pounds per Cubic Foot							
	Slab A	Slab B	Slab C	Slab D	Slab E	Slab F	Slab G	Slab H
1	101	132	115	94	110	128	114	109
2	109	123	114	101	106	121	113	106
3	112	136	112	110	105	123	126	105
4	106	130	112	110	94	128	119	108
5	108	119	101	102	101	132	133	99
6	98	135	110	112	101	133	137	104
7	110	141	115	106	111	133	127	108
8	109	131	113	113	105	120	124	108
9	106	119	108	110	95	131	122	113
10	106	120	117	113	101	133	113	119
11	96	115	112	114	113	131	121	104
12	95	133	109	114	95	134	125	113
13	109	131	101	106	95	123	119	112
14	95	125	109	112	96	115	133	117
15	102	130	109	106	106	124	133	100
16	109	132	101	106	113	132	134	116
Type Subbase	A-2A	A-3A	A-2A	A-2A	A-2A	A-3A	Cement Treated	Slag

Table C-5. Record of Test Slab Pours

Slab	Date Poured	Slump (inches)	Air Content (percent)	Concrete Strength Age (days)	Concrete Strength Strength (psi)	Remarks
A	6/22/70	3.5	None Taken	32	3406	One radioactive source in each test site. Five aluminum plates in outer foot.
B	6/29/70	5.5	4.5	25	3244	One radioactive source in each test site. Three aluminum plates under mesh portion in the outer foot.
C	7/ 2/70	1.5	4.25	32	3070	One radioactive source in each test site. Three aluminum plates in outer foot.
D	7/ 8/70	2.0	4.5	30	3210	Two radioactive sources in test sites 1, 4, 6, 7, 10, 11, 13, and 16.
E	7/13/70	1.75	5.0	25	2686	Four radioactive sources in test sites 1, 4, 13, and 16. Sources in test sites 4 and 16 are collimated aluminum foil placed under test sites 1, 2, 3, and 4.
F	7/16/70	1.5	4.3	32	4117	Four radioactive sources in test sites 1, 4, 13, and 16.

Table C-5. Continued

Slab	Date Poured	Slump (inches)	Air Content (percent)	Concrete Strength Age (days)	Concrete Strength Strength (psi)	Remarks
G	7/20/70	0.75	4.6	28	4573	Four radioactive sources in test sites 1, 7, and 16. Five radioactive sources in test sites 4, 11, and 13.
H	7/23/70	3.0	5.0	25	3183	Six radioactive sources in test sites 4, 13, amd 11. Four radioactive sources in test sites 1, 6, 7, and 16. Aluminum foil placed under test sites 2, 7, 10, and 15.

Table C-6. Composition of Test Areas Used in Thickness and Reinforcement Measurements

Thickness Measurements		Reinforcement Measurements	
Area No.	Test Sites	Area No.	Test Sites
A-1	9, 10, 15, 16	A-1	11, 14
A-2	11-14	A-2	12, 13
A-3	1, 2, 7, 8	A-3	3, 6
A-4	3-6	A-4	4, 5
B-1	1, 2, 7-10, 15, 16	B-1	4, 5, 12, 13
B-2	3-6, 11-14	B-2	3, 6, 11, 14
C-1	9, 10, 15, 16	C-1	11, 14
C-2	11-14	C-2	12, 13
C-3	1, 2, 7, 8	C-3	3, 6
C-4	3-6	C-4	4, 5
D-1	1, 2, 7-10, 15, 16	D-1	4, 5, 12, 13
D-2	3-6, 11-14	D-2	3, 6, 11, 14
E-1	9, 10, 15, 16	E-1	11, 14
E-2	11-14	E-2	12, 13
E-3	1, 2, 7, 8	E-3	3, 6
E-4	3-6	E-4	4, 5
F-1	9, 10, 15, 16	F-1	11, 14
F-2	11-14	F-2	12, 13
F-3	1, 2, 7, 8	F-3	3, 6
F-4	3-6	F-4	4, 5
G-1	9, 10, 15, 16		
G-2	11-14		
G-3	1, 2, 7, 8		
G-4	3-6		
H-1	1, 2, 7-10, 15, 16		
H-2	3-6, 11-14		

Table C-7. Summary of Slab Thickness Measurements

	Levels		Cores-Std.		Cores-1/8		Cores-1		Nuclear (C)		Resistivity		Ult. Son.-1		Ohio State gage		Eddy Cur.	
Test Area	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
A-1	6.41	0.228	6.53	0.399	6.45	0.381	6.58	0.358	5.99	1.098	7.29	0.523	7.12	2.393	6.55	0.248		
A-2	6.76	0.096	6.77	0.250	6.71	0.242	6.83	0.219	6.42	1.675	7.50	0.852	7.23	2.742	6.80	0.505		
A-3	6.05	0.122	6.15	0.240	6.14	0.205	6.27	0.194	6.69	0.886	7.23	0.756	7.64	2.286	6.90	0.330		
A-4	6.32	0.155	6.34	0.207	6.30	0.212	6.44	0.215	6.36	0.956	6.72	0.927	7.91	2.495	7.51	0.529		
B-1	8.39	0.354	8.31	0.451	8.27	0.449	8.32	0.431	7.42	1.165	7.40	0.858	8.38	1.970	8.32	0.136		
B-2	7.91	0.233	7.97	0.328	7.93	0.315	7.98	0.314	7.76	1.192	7.50	0.784	8.29	1.809	8.00	0.071		
C-1	9.32	0.171	9.74	0.266	9.73	0.282	9.84	0.284	10.20	1.307	10.14	0.803	8.72	1.198	9.78	0.320		
C-2	9.39	0.156	9.71	0.196	9.58	0.199	9.79	0.198	10.66	1.284	10.66	1.024	8.65	0.955	9.89	0.389		
C-3	9.37	0.046	9.62	0.219	9.50	0.209	9.69	0.220	10.41	1.395	10.24	0.875	9.01	1.400	9.90	0.142		
C-4	9.55	0.081	9.73	0.168	9.71	0.162	9.82	0.167	9.81	1.099	10.34	1.059	8.76	1.177	10.02	0.134		
D-1	9.46	0.307	9.79	0.264	9.59	0.299	9.83	0.278	9.93	1.040	9.99	0.740	8.74	2.532	10.84	0.346	See Table C-25	
D-2	9.92	0.328	10.15	0.313	10.11	0.292	10.21	0.277	10.59	1.262	10.19	0.679	8.62	2.466	10.83	0.848		
E-1	13.19	0.649	13.36	0.713	13.28	0.668	13.43	0.672	12.38	1.382	12.48	0.554	8.16	1.028	NO DATA			
E-2	13.09	0.690	13.36	0.772	13.33	0.716	13.47	0.736	11.60	1.715	12.56	0.915	8.21	1.061	NO DATA			
E-3	13.73	0.296	13.80	0.585	13.76	0.483	13.89	0.505	15.28	0.499	12.34	1.033	8.24	0.997	12.70	0.283		
E-4	13.40	0.313	13.46	0.780	13.48	0.646	13.61	0.683	13.40	2.298	12.28	0.786	8.09	1.139	10.73	1.418		
F-1	12.89	0.174	12.72	0.231	12.70	0.224	12.74	0.253	11.80	1.809	12.72	0.909	8.10	2.221	13.27	0.377		
F-2	12.94	0.161	12.71	0.231	12.69	0.240	12.77	0.277	12.68	0.838	12.67	0.695	8.21	2.304	12.54	1.562		
F-3	13.01	0.067	12.95	0.146	12.93	0.129	13.03	0.165	12.35	0.971	13.02	0.585	8.35	2.214	11.42	1.951		
F-4	12.93	0.122	12.80	0.248	12.31	0.259	12.97	0.281	11.20	2.093	13.06	0.793	8.50	2.832	12.71	0.768		

Table C-7. Continued

	Levels		Cores-Std.		Cores-1/8		Cores-1		Nuclear (C)		Resistivity		Ult. Son.-1		Ohio State gage		Eddy Cur.	
Test Area	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
G-1	10.07	0.222	9.98	0.327	9.92	0.363	9.97	0.364	8.93	0.655	9.93	0.812	8.26	1.088	10.15	2.323	See Table C-25	
G-2	12.85	0.312	12.82	0.440	12.81	0.483	12.85	0.479	12.09	0.664	12.50	0.700	7.69	1.178	11.94	1.661		
G-3	10.84	0.106	10.64	0.235	10.62	0.227	10.65	0.216	9.13	0.232	9.90	0.903	8.24	1.551	9.41	1.054		
G-4	13.42	0.172	13.35	0.337	13.35	0.370	13.38	0.368	14.83	1.763	12.91	0.923	8.30	1.738	12.07	0.289		
H-1	11.07	0.331	11.17	0.851	11.13	0.848	11.19	0.851	9.23	0.787	10.32	1.086	7.73	1.986	NO DATA			
H-2	14.18	0.332	14.13	0.360	14.14	0.355	14.19	0.345	13.28	1.263	13.05	0.547	8.05	2.048	NO DATA			

Table C-8. Test Site Thickness by Differential Level Readings

Slab	Site 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	5.94	6.16	6.18	6.19	6.48	6.42	6.15	5.95	6.09	6.41	6.73	6.63	6.82	6.84	6.79	6.36
B	8.44	8.80	8.15	7.65	7.74	8.04	8.68	8.44	8.20	8.61	8.26	7.80	7.64	7.96	8.26	7.67
C	9.37	9.36	9.64	9.49	9.59	9.47	9.32	9.43	9.29	9.09	9.18	9.39	9.55	9.45	9.45	9.45
D	9.26	9.44	9.72	9.90	9.58	9.50	9.26	9.03	9.27	9.69	9.83	10.13	10.42	10.26	9.91	9.78
E	13.83	13.37	13.07	13.26	13.80	13.47	13.65	14.07	13.53	13.92	13.38	13.86	12.84	12.26	12.51	12.80
F	12.92	13.03	12.87	12.80	12.97	13.08	13.08	13.00	12.97	13.08	13.10	13.05	12.81	12.79	12.80	12.69
G	10.98	10.87	13.43	13.57	13.51	13.18	10.76	10.76	10.35	10.13	12.97	13.22	12.72	12.50	9.84	9.96
H	10.72	10.49	13.65	13.71	14.25	14.14	10.31	10.97	11.26	11.27	14.35	14.43	14.50	14.44	11.38	11.42

Table C-9. Difference between Differential Level Readings and Core Length Measurements

Test Section	Difference
A-1	-0.04
A-2	+0.05
A-3	-0.09
A-4	+0.02
B-1	+0.12
B-2	-0.02
C-1	-0.41
C-2	-0.29
C-3	-0.23
C-4	-0.16
D-1	-0.23
D-2	-0.19
E-1	-0.09
E-2	-0.24
E-3	-0.03
E-4	-0.08
F-1	+0.19
F-2	+0.25
F-3	+0.08
F-4	+0.12
G-1	+0.15
G-2	+0.04
G-3	+0.22
G-4	+0.07
H-1	-0.06
H-2	+0.04

No. +	12	No. crit. (95% level)	7
No. -	14	Significant (95% level)?	No
No. 0	0	Avg. deviation, inches	-0.0312

Table C-10. Gamma Ratio Compared with Slab Thickness

Slab	Site	γ_1/γ_2	Thickness	Slab	Site	γ_1/γ_2	Thickness
A	1	3.15	5.92	C	1	2.33	9.38
	2	2.83	6.25		2	2.52	9.22
	3	2.71	6.26		3	2.44	9.54
	4	2.69	6.29		4	2.81	9.42
	5	3.08	6.53		5	2.30	9.70
	6	2.67	6.43		6	2.10	9.44
	7	2.58	6.11		7	2.42	9.32
	8	2.63	5.90		8	2.15	9.48
	10	2.06	6.32		9	2.32	9.28
	11	2.48	6.73		10	2.31	9.02
	12	2.15	6.62		11	2.09	9.17
	14	2.37	6.74		12	2.62	9.41
	15	3.02	6.74		13	2.59	9.58
	16	2.30	6.19		14	2.81	9.58
B	1	2.47	8.32		15	2.51	9.58
	2	2.45	9.10		16	2.26	9.46
	3	2.20	8.39	D	1	2.56	9.26
	4	2.35	7.52		1	2.65	9.26
	5	2.20	7.69		4	2.68	9.89
	6	2.49	8.16		4	2.30	9.89
	7	1.99	8.90		6	2.67	9.49
	8	2.21	8.40		6	2.37	9.49
	9	2.56	8.32		7	2.72	9.16
	10	2.44	8.70		7	2.61	9.16
	11	3.02	8.32		10	2.22	9.71
	12	2.39	7.75		10	2.69	9.71
	13	1.90	7.61		11	2.94	9.88
	14	2.28	7.96		11	2.31	9.88
	15	2.28	8.36		13	2.76	10.49
	16	2.62	7.81		13	2.00	10.49
					16	2.29	9.79
					16	2.60	9.79

Correlation coefficient = -0.203
n = 62 d.f. = n-2 = 60
Crit. corr. coeff. (95%) = 0.250
Conclusion: No significant correlation

Table C-11. Differential Level Thicknesses Compared with Ratemeter and Counter Readings

Test Site	Diff. Level	Ratemeter Reading	Ratemeter Difference	Counter Reading	Counter Difference
A-1	5.9	6.0	-0.1	5.6	+0.3
A-2	6.2	7.0	-0.8	7.6	-1.4
A-3	6.2	5.0	+1.2	6.0	+0.2
A-4	6.2	7.0	-0.8	7.6	-1.4
A-5	6.5	7.5	-1.0	7.4	-0.9
A-6	6.4	6.0	+0.4	6.9	-0.5
A-7	6.2	5.5	+0.7	5.0	+1.2
A-8	6.0	6.0	0.0	7.8	-1.8
A-9	6.1	4.0	+2.1	5.5	+0.6
A-10	6.4	4.0	+2.4	4.2	+2.2
A-11	6.7	5.9	+0.8	5.9	+0.8
A-12	6.6	6.0	+0.6	6.0	+0.6
A-13	6.8	8.3	-1.5	11.8	-5.0
A-14	6.8	6.0	+0.8	5.3	+1.5
A-15	6.8	7.3	-0.5	7.9	-1.1
A-16	6.4	4.0	+2.4	5.1	+0.7
E-1	13.8	12.3	+1.5	15.0	-1.2
E-4	13.3	13.4	-0.1	16.8	-3.5
E-13	13.8	13.4	+0.4	14.0	-0.2
E-15	12.8	13.3	-0.5	14.4	-1.6
E-1	12.8	13.0	+0.8	14.9	-1.1
E-4	13.3	13.3	0.0	12.8	+0.5
E-13	13.8	12.3	+1.5	10.0	+3.8
E-15	12.8	12.0	+0.8	12.0	+0.8

	Ratemeter	Counter
Mean deviation	+0.46	-0.27
Std. dev.	1.05	1.81
No. of +	14	12
No. of -	8	12
n-crit.	5	6
Significant (95%)?	No	No

Table C-12. Summary of Analyses of Variance

Factor	Resistivity F	Resistivity d.f.	Resistivity Sig.	Nuclear (Counter) F	Nuclear (Counter) d.f.	Nuclear (Counter) Sig.	Ult. Son.-1 F	Ult. Son.-1 d.f.	Ult. Son.-1 Sig.	Pachometer F	Pachometer d.f.	Pachometer Sig.
Surface	0.575	1/59	61	1.756	1/60	81	0.139	1/76	29	21.07	1/120	100
Reinforcement	0.574	1/59	55	0.378	1/60	54	1.151	1/76	71			
Interaction: Surf. & Reinf.	1.156	1/59	71	3.359	1/60	93	0.273	1/76	40			
Strength	10.60	1/59	100	2.148	1/52	85	5.588	1/68	98			
Interaction: Str. & Reinf.	2.572	1/59	89	0.003	1/52	4	0.074	1/68	21			
Thickness	1.609	1/30	79	0.371	1/30	45	14.56	1/41	100			
Bottom Condition	70.8	1/28	100	18.7	1/30	100	7.609	1/37	99			
Membrane	1.421	1/30	76	9.05	1/30	99	1.643	1/44	79			
Base Type	13.69	2/45	100	22.5	2/29	100	11.50	2/48	100			
Bar Size											1/120	100
Interaction: Bar Size & Surf.										13.15	1/120	100
Bar Depth											1/122	100
Bar Spacing										40.19	1/158	100
No. Layers of Bars										47.33	1/126	100

Table C-13. Analyses of Thickness Measurements

Test Section	Comparison of Readings on Fresh Concrete with the Average of all Readings						Comparison of Average Instrumental Readings with Differential Level Readings							
	Nuclear (C)		Resistivity		Ult. Son.-1		Nuclear (C)		Resistivity		Ult. Son.-1		Ohio State gage	
	d.f.	t	d.f.	t	d.f.	t	d.f.	t	d.f.	t	d.f.	t	d.f.	t
A-1	18	0.571	18	1.572	25	0.583	18	0.767	18	3.206*	25	0.581	7	0.772
A-2	18	1.281	18	0.724	25	0.725	18	0.406	18	1.704	25	0.341	6	0.175
A-3	18	0.926	18	0.166	25	1.291	18	1.454	18	3.064*	25	1.367	6	4.737*
A-4	18	1.517	18	0.289	25	1.361	18	0.095	18	0.839	25	1.264	6	0.254
B-1	38	0.932	38	1.763	38	3.582*	38	2.300*	38	3.164*	38	0.009	11	0.390
B-2	38	1.554	38	1.375	38	3.516*	38	0.314	38	1.433	38	0.596	8	0.548
C-1	18	0.562	18	1.349	22	1.211	18	1.360	18	2.003	22	0.983	6	2.515*
C-2	18	0.440	16	2.411*	22	1.372	18	1.999	17	2.427*	22	1.535	4	2.402
C-3	18	1.090	18	0.708	22	1.063	18	1.513	18	1.957	22	0.505	8	7.095*
C-4	18	0.853	18	0.860	22	0.851	18	0.476	18	1.473	22	1.314	6	6.090*
D-1	26	2.124*	38	1.203	40	4.275*	30	1.271	38	1.792	40	0.788	14	8.461*
D-2	26	0.454	38	0.351	42	4.284*	30	1.471	38	1.080	42	1.476	13	2.822*
E-1	3	1.311	18	0.427	18	0.599	6	1.068	18	2.222*	18	9.235*	NO	DATA
E-2	3	1.252	19	1.801	18	0.900	6	1.607	19	1.067	18	8.654*	NO	DATA
E-3	3	0.493	18	0.604	18	1.446	6	5.329*	18	2.620*	18	10.694*	4	4.068*
E-4	3	1.324	18	0.073	18	0.851	6	0.000	18	2.748*	18	9.078*	6	3.687*
F-1	3	0.049	18	0.802	20	2.167*	6	1.194	18	0.351	20	4.226*	6	1.845
F-2	3	0.827	17	0.392	20	2.378*	6	0.615	17	0.750	20	4.028*	6	0.506
F-3	3	0.507	18	0.637	22	2.281*	6	1.351	18	0.038	22	4.135*	6	1.631
F-4	3	1.069	18	1.559	22	1.959	6	1.651	18	0.327	22	3.073*	6	0.573
G-1	3	0.580	18	1.068	18	0.908	6	3.312*	18	0.348	18	3.246*	6	0.069
G-2	8	1.289	18	1.362	18	1.666	10	2.150	18	0.968	18	8.532*	6	1.083
G-3	8	0.127	18	1.728	18	1.381	10	13.860*	18	2.044	18	3.284*	6	2.702*
G-4	3	1.332	18	0.255	18	0.446	6	1.563	18	1.093	18	5.771*	5	7.860*
H-1	13	0.783	38	1.540	33	3.111*	18	6.213*	38	1.926	33	4.638*	NO	DATA
H-2	18	1.091	38	1.093	34	3.504*	22	1.931	38	5.597*	34	8.352*	NO	DATA

*Significant at the 95 percent level or higher.

Table C-14. Mean Standard Deviations for Test Methods

Test for	Test Method	Mean Std. Dev.
Slab thickness	Differential levels	0.3465
	Nuclear (Counter)	1.2049
	Resistivity	0.8123
	Ult. Son.-1	1.8004
	Ohio State gage	0.7676
	Eddy Cur. Prox.	0.2475
	Coring - Pa. Std.	0.3675
	Coring - 1/8" Ball	0.3560
	Coring - 1" Flat	0.3569
Depth of rebars	Cores	0.2378
	Pachometer	0.1588
	Resistivity	0.7119
Spacing of rebars	Cores	0.3893
	Pachomater	0.3582
Depth of mesh	Cores	0.6156
	Pachometer	0.3372
	Resistivity	0.7172
	Eddy Cur. Prox.	0.2942

Table C-15. Comparison of Indicated Thickness

Test Site	Thickness in Inches																	
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	6.7	6.5	5.9							8.8	9.7	9.3	13.0	14.4	13.8			
4	8.1	6.5	6.2							9.0	10.4	9.9	12.6	13.4	13.3	11.6	11.2	12.8
6	8.0	6.4	6.4	7.4	8.0	8.0	10.2	9.5	9.5									
7	6.3	6.3	6.2				9.9	9.9	9.3									
10				8.4	8.4	8.6												
13										9.7	10.3	10.4	12.9	12.0	12.8			
16										9.8	10.1	9.8	11.2	12.5	12.8	12.3	12.7	12.7

1 - special tests, three runs with five points

2 - normal tests, four to six runs with three points

3 - measured thickness by differential levels

Table C-16. Reproducibility of Nuclear Gage

	Slab A						Slab D						Slab E					
	Site 2			Site 7			Site 1			Site 16			Site 4			Site 16		
Height	0	3	6	0	3	6	0	3	6	0	3	6	0	3	6	0	3	6
Counts Per Minute	16380	8890	5290	16590	7470	3400	7380	3480	1660	11070	4240	1740	2260	900	550	3780	1570	930
	17170	10030	6680	17210	7500	3110	7010	2940	1930	7200	3940	1760	2050	780	490	3810	1430	1050
	17250	10680	6570	17520	7840	3140	6920	2850	1820	9940	3620	1930	1930	920	470	3590	1370	1060
	17820	10260	6220	18380	7510	2890	7080	2560	1830	9830	3570	1690	2030	910	500	3560	1480	1000
	17380	10370	6410	18670	8000	2890	6776	2770	2100	10440	3630	1960	2120	950	480	3750	1620	1100
	17870	10650	6060	18460	8160	2990	6520	2530	2040	9160	3700	1910	2060	960	560	3480	1420	950
	19370	10750	6730	18210	7900	3030	6100	2840	1800	9210	3560	1900	2160	890	430	3990	1680	1010
	19980	10710	6140	19060	8370	3100	6520	2730	1940	9180	3270	1940	2140	1050	570	3390	1620	1070
	18140	11300	6480	18530	8240	3100	6180	2360	1820	9300	3100	1840	1900	870	780	3890	1550	1040
	18910	10030	6340	18480	7870	3300	6620	2450	1880	8920	3460	2180	2010	950	470	3320	1500	950
Avg.	18207	100337	6226	18111	7886	3095	6710	2751	1882	9425	3609	1885	2066	918	540	3656	1524	1016
S.D.	1103	619	400	760	319	162	402	319	127	1031	319	140	108	70	106	222	101	58
C.V.	6.1%	6.0%	6.4%	4.2%	4.0%	5.2%	6.0%	11.6%	6.8%	10.9%	6.9%	7.4%	5.2%	7.6%	19.6%	6.1%	6.6%	5.7%

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Table C-17. Collimation Effects

Test Site	cpm with Detector @ 6"	cpm with gage @ 6"
B-10	1820	2435
D-7	2015	3000

Table C-18. Mean Difference between Instrument Reading and Differential Level Determinations

Test for	Test Method	Mean Diff.[a]
Slab Thickness	Nuclear (counter)	+0.23
	Resistivity	+0.06
	Ult. Son.-1	+2.43
	Ohio State gage	+0.12
	Eddy cur. prox.	-0.25[b]
Depth of rebars	Pachometer	(c)
	Resistivity	+0.11
Spacing of rebars	Pachometer	+0.05
Depth of mesh	Pachometer	+1.05
	Resistivity	+0.68
	Eddy cur. prox.	+1.25

(a) Differential level determination minus instrument reading.

(b) Does not include data from Slab H.

(c) Varies with depth of bars -- for 2 in. depth: +0.15 in.
for 4 in. depth: +0.92 in.
for 6 in. depth: +2.38 in.

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Table C-19. Resistivity Special Test No. 1

Test Site	Slab Thickness, in.			Reinforcement Depth, in. Top Layer			Bottom Layer			Type of Reinf.
	1	2	3	1	2	3	1	2	3	
G-1	10.3	10.0	11.0							
H-8	10.0	10.0								
D-9	10.5	10.5	10.6							
D-5	11.1	11.1	10.0	4.0	4.7	4.1	7.4	6.5	6.5	mesh
B-10	6.5	7.0	7.0							
B-6	6.3	7.0	6.8	3.0	3.0	2.5				mesh
C-7	9.0	10.0	10.0							
A-15	6.0	6.0	6.0							
C-3	9.0	9.7	9.0	4.8	5.0	5.0				bar

Table C-20. Resistivity Special Test No. 2

Test Site	Slab Thickness, in.				Reinforcement Depth, in.				Type of Reinf.
	1	2	3	4	1	2	3	4	
G-1	9.0	10.0	10.0						
G-5	11.5	12.0	11.0	13.0					
F-7	13.0	11.0	12.0	12.0					
F-6	12.3	12.0	11.5	12.2	2.3	2.0	2.2	2.0	bar
A-6	8.1	7.0	6.4	6.6	2.4	2.0	2.4	2.0	bar
A-15	7.5	6.5	7.0	7.0					
E-3	11.0	11.0	11.1	10.0	2.0	2.2	2.0	3.0	bar
B-6	5.7	6.0	6.5	7.0	2.3	2.8	2.3	2.0	mesh
B-10	8.0	7.0	8.8	8.5					
C-7	9.0	9.0	8.6	8.0					
C-3	9.0	10.0	8.3	9.0	4.0	4.6	4.3	4.5	bar

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Table C-21. Summary of Data for Special Tests on Ultrasonic-1

Test Site	Date	Operator	Time	Thickness Determinations Mean	No.	C.V.
C-1	7/10	1	10:30	9.34	5	14.6%
			13:30	6.94	5	3.6%
		2	14:30	5.07	7	7.9%
C-4	7/10	1	10:30	8.44	5	7.7%
			13:30	7.20	5	6.0%
		2	14:30	4.92	5	10.7%
C-13	7/10	1	10:30	8.20	5	7.3%
			13:30	6.86	5	7.5%
C-16	7/10	1	10:30	8.58	5	22.6%
			13:30	7.42	5	4.6%
D-1	7/14	?	10:30	9.34	10	15.4%
D-4	7/14	?	10:30	8.25	10	6.1%
D-13	7/15	3	13:30	9.14	12	3.8%
	7/20	3	11:00	9.69	10	16.3%
		4	14:30	8.73	9	12.1%
D-16	7/15	3	13:30	8.66	10	3.4%
	7/20	3	11:00	8.84	10	15.4%
		4	14:30	10.11	9	25.3%

Table C-22. T-Test for Effect of Time of Day

Test Site	Date	Oper.	D.F.	t	Sign. @ 95%?
C-1	7/10	1	8	3.873	Yes
C-4	7/10	1	8	3.544	Yes
C-13	7/10	1	8	3.798	Yes
C-16	7/10	1	8	1.317	No
D-13	7/15-20	3	20	-1.174	No
D-16	7/15-20	3	18	-0.410	No

Table C-23. T-Test for Effect of Operator

Test Site	Date	Time	D.F.	t	Sign. @ 95%?
C-1	7/10	13:30-14:30	10	9.191	Yes
C-4	7/10	13:30-14:30	8	7.505	Yes
D-13	7/15-20	13:30-14:30	19	1.258	No
D-16	7/15-20	13:30-14:30	17	-1.784	No

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Table C-24. Effect of Aluminum Foil on Thickness Determinations with Various Instruments

Instrument	Test Area	Aluminum Foil Number	Average	Std. Dev.	No Aluminum Foil Number	Average	Std. Dev.	d.f.	t
Nuclear (Counter)	1	Insufficient Data							
	2	Insufficient Data							
	3	4	8.98	0.690	8	9.36	0.843	10	0.792
Resistivity	1	8	11.94	0.939	8	12.61	1.219	14	0.217
	2	8	12.05	0.872	8	12.51	0.664	14	1.196
	3	16	10.21	1.089	16	10.43	1.107	30	0.556
Ult. Son.-1	1	8	8.35	1.019	8	8.14	1.024	14	0.423
	2	8	8.18	1.432	8	7.99	0.840	14	0.324
	3	11	8.33	1.099	11	8.65	1.431	20	0.579
Ohio State gage	1	Insufficient Data							
	2	2	11.20	2.263	2	10.25	0.071	2	0.593
	3	Insufficient Data							

Table C-25. Comparison of Eddy Current Proximity Gage Measurements of Slab Thickness with Core Lengths

SLAB	READING	a	b	c	d	e
A	1	6.00	6.20	5.90	6.50	6.90
	2	5.75	5.95	5.85	6.50	6.10
	3	5.80	6.00	5.90	7.30	6.70
	4	6.10	5.95	6.10	7.30	6.30
	Mean	5.91	6.03	5.94	6.90	6.50
	Standard deviation	0.165	0.119	0.111	0.462	0.365
	Core meas. (1/8" ball)	5.93	6.11	5.83	6.74	6.29
	Difference	-0.02	-0.08	+0.11	+0.16	+0.21
	Student's t for diff.	0.275	1.530	2.254	0.788	1.311
C	1	9.15	9.35	10.15		
	2	9.10	9.40	9.95		
	3	9.00	9.20	10.00		
	4	9.20	9.20	10.00		
	Mean	9.11	9.29	10.03		
	Standard deviation	0.085	0.103	0.087		
	Core meas. (1/8" ball)	9.44	9.37	9.36		
	Difference	-0.33	-0.08	+0.67		
	Student's t for diff.	8.108*	1.610	15.262*		
E	1	14.20	13.85	14.10	13.90	
	2	13.75	14.20	14.10	14.10	
	3	14.00	13.95	14.10	13.75	
	4	13.35	13.15	13.25	13.00	
	Mean	13.83	13.79	13.89	13.69	
	Standard deviation	0.366	0.450	0.425	0.480	
	Core meas. (1/8" ball)	13.78	13.03	12.77	13.17	
	Difference	-0.05	+0.76	+1.12	+0.52	
	Student's t for diff.	0.290	3.753*	7.783*	2.784*	
H	1	9.10	9.20	9.20	9.20	
	2	9.20	9.20	9.80	9.60	
	3	9.15	9.25	8.90	9.25	
	4	9.25	9.40	9.60	9.40	
	Mean	9.18	9.26	9.38	9.36	
	Standard deviation	0.065	0.095	0.403	0.180	
	Core meas. (1/8" ball)	10.39	10.75	11.20	11.28	
	Difference	-1.21	-1.49	-1.82	-1.92	
	Student's t for diff.	19.485*	33.559*	10.288*	22.300*	

*Significant difference exists at 95 percent level.

Table C-26. Measurements of Depth of Reinforcing Bars

TEST AREA	CORES Avg.	CORES Std. dev.	PACHOMETER Avg.	PACHOMETER Std. dev.	PACHOMETER t for diff.	RESISTIVITY Avg.	RESISTIVITY Std. dev.	RESISTIVITY t for diff.
A-1	2.21	0.186	2.06	0.146	2.297*	2.35	0.444	0.721
A-2	2.24	0.125	2.31	0.120	1.326	2.42	0.458	0.927
A-3	1.99	0.137	1.90	0.094	2.101*	2.66	0.370	4.191*
A-4	2.17	0.184	2.25	0.137	1.296	2.37	0.273	1.584
C-1	4.20	0.117	3.35	0.164	12.247*	4.24	0.682	0.140
C-2 (top)	4.39	0.154	3.38	0.177	12.269*	3.53	0.730	2.558*
C-2 (btm)	6.38	0.207	NO	DATA		6.05	1.364	0.528
C-3	4.31	0.115	3.46	0.147	11.275*	4.29	0.666	0.058
C-4 (top)	4.29	0.247	3.34	0.252	9.335*	3.93	0.900	1.021
C-4 (btm)	6.23	0.193	NO	DATA		6.36	0.936	0.332
E-1	6.71	0.714	3.96	0.129	21.150*	6.67	1.284	0.058
E-2	6.52	0.224	5.02	0.133	19.340*	5.99	0.833	1.223
E-3	6.94	0.518	4.02	0.095	29.220*	6.35	0.749	1.415
E-4	7.34	0.346	4.99	0.182	21.953*	7.18	0.994	0.306
F-1	2.93	0.353	2.68	0.232	1.919	2.41	0.285	2.763*
F-2 (top)	2.88	0.274	2.61	0.194	2.516*	2.77	0.650	0.318
F-2 (btm)	4.85	0.192	NO	DATA		5.13	1.448	0.376
F-3	2.76	0.154	2.53	0.161	2.696*	2.84	0.469	0.325
F-4 (top)	2.95	0.173	2.63	0.178	3.474*	2.73	0.359	1.143
F-4 (btm)	4.97	0.143	NO	DATA		4.70	0.723	0.718

*Significant difference exists between core measurements and instrument measurements at 95 percent level.

Table C-27. Reinforcing Bar Depth by Pachometer: Comparison of Readings on Fresh Concrete with the Average of All Readings

TEST SECTION	DEGREES OF FREEDOM	t
A-1	58	0.963
A-2	58	0.587
A-3	58	0.401
A-4	58	0.469
C-1	52	0.303
C-2	58	0.925
C-3	58	0.314
C-4	57	2.292*
E-1	38	0.886
E-2	38	1.657
E-3	30	0.378
E-4	38	1.310
F-1	38	0.351
F-2	38	0.219
F-3	38	0.201
F-4	38	0.195

*Significant at 95 percent level or higher.

Table C-28. Reinforcing Bar Spacing Measured by Pachometer

SLAB	RUN	a-1	b-1	c-1	d-1	e-1	a-2	b-2	c-2	d-2	e-2
A	1	5.38	5.88	13.13	5.88	5.88	4.88	5.50	14.00	6.75	5.25
	2	5.00	6.13	13.25	6.25	5.50	5.00	5.88	13.75	6.50	5.38
	3	5.50	6.00	13.00	6.50	5.38	5.00	6.13	13.38	6.50	5.50
	4	5.38	5.88	13.38	6.38	5.50	4.88	5.50	14.25	6.50	5.38
	Mean	5.32	5.97	13.19	6.25	5.57	4.94	5.75	13.85	6.56	5.38
	Standard deviation	0.217	0.119	0.163	0.268	0.217	0.069	0.309	0.371	0.125	0.102
	Core hole meas.	5.50	6.00	12.50	6.25	5.50	4.75	5.75	14.00	6.50	5.50
	Difference	-0.18	-0.03	+0.69	0.00	+0.07	+0.19	0.00	-0.15	+0.06	-0.12
	Student's t for diff.	0.743	0.226	3.802*	0.000	0.289	2.458	0.000	0.362	0.433	1.064
C	1	4.50	5.50	13.88	4.75	6.63	5.00	5.63	12.75	5.13	7.13
	2	5.50	5.50	13.50	5.50	5.25	5.13	5.50	13.25	5.38	7.50
	3	5.13	5.75	11.13	6.25	7.50	4.62	5.75	13.00	5.13	7.75
	4	5.63	5.63	12.38	5.75	6.13	5.63	5.88	12.38	6.00	5.75
	Mean	5.19	5.60	12.72	5.56	6.38	5.10	5.69	12.85	5.41	7.03
	Standard deviation	0.506	0.120	1.238	0.625	0.941	0.417	0.163	0.371	0.411	0.892
	Core hole meas.	5.75	5.75	12.50	6.25	6.00	5.75	5.75	12.75	5.75	6.75
	Difference	-0.56	-0.15	+0.22	-0.69	+0.38	-0.65	-0.06	+0.10	-0.34	+0.28
	Student's t for diff.	0.988	1.119	0.159	0.988	0.361	1.395	0.331	0.241	0.740	0.281
E	1	NO DATA					NO DATA				
	2										
	3										
	4	8.50	15.25	8.75			8.25	16.25	8.00		
	Core hole meas.	8.25	16.25	8.00			8.25	16.25	8.00		
	Difference	+0.25	-1.00	+0.75			0.00	0.00	0.00		
F	1	9.00	15.00	8.13			8.75	15.13	8.88		
	2	8.63	15.13	8.38			8.75	15.50	8.75		
	3	8.56	15.44	8.19			8.50	15.38	8.56		
	4	8.50	15.38	8.50			9.25	15.00	8.50		
	Mean	8.67	15.24	8.30			8.81	15.25	8.67		
	Standard deviation	0.225	0.208	0.171			0.315	0.228	0.175		
	Core hole meas.	8.75	15.50	8.25			9.00	15.25	8.50		
	Difference	-0.08	-0.26	+0.05			-0.19	0.00	+0.17		
	Student's t for diff.	0.318	1.119	0.262			0.542	0.000	0.873		

SLAB	RUN	a-3	b-3	c-3	d-3	e-3	a-4	b-4	c-4	d-4	e-4
A	1	4.88	5.13	14.50	6.38	5.63	5.13	5.75	13.00	6.50	5.38
	2	5.13	5.88	14.75	6.38	5.44	5.63	5.63	13.63	6.13	5.56
	3	5.25	6.00	13.38	6.25	5.75	5.63	6.00	12.88	6.00	5.88
	4	5.25	5.00	15.00	6.50	5.50	5.25	6.13	12.94	6.50	5.56
	Mean	5.13	5.50	14.41	6.38	5.58	5.41	5.88	13.11	6.28	5.60
	Standard deviation	0.174	0.510	0.715	0.102	0.138	0.259	0.228	0.348	0.257	0.208
	Core hole meas.	5.00	5.75	14.25	6.50	5.50	5.50	5.75	13.00	6.50	5.50
	Difference	+0.13	-0.25	+0.16	-0.12	+0.08	-0.09	+0.13	+0.11	-0.22	+0.10
	Student's t for diff.	0.667	0.438	0.200	1.064	0.517	0.312	0.509	0.282	0.768	0.430
C	1	5.00	5.75	13.13	5.25	6.83	5.00	6.25	12.50	6.13	6.00
	2	4.25	6.38	12.38	5.50	6.75	5.00	6.25	13.25	5.50	6.00
	3	5.38	5.75	13.00	5.00	7.63	5.75	5.75	12.13	6.00	6.13
	4	5.50	5.00	12.38	5.88	6.13	6.00	5.75	12.25	5.38	6.13
	Mean	5.03	5.72	12.72	5.41	6.84	5.44	6.00	12.53	5.75	6.07
	Standard deviation	0.564	0.564	0.399	0.375	0.615	0.315	0.289	0.503	0.368	0.075
	Core hole meas.	5.75	6.00	13.00	5.75	7.00	5.75	6.00	12.00	6.00	6.25
	Difference	-0.72	-0.28	-0.18	-0.34	-0.16	-0.31	0.00	+0.53	-0.25	-0.18
	Student's t for diff.	1.143	0.444	0.627	0.811	0.233	0.539	0.000	0.944	0.607	2.153
E	1	NO DATA					NO DATA				
	2										
	3										
	4	8.25	15.75	7.75			7.75	16.50	7.75		
	Core hole meas.	8.25	15.50	8.00			8.25	16.25	8.00		
	Difference	0.00	+0.25	-0.25			-0.50	+0.25	-0.25		
F	1	8.25	16.25	8.25			8.50	16.50	8.00		
	2	8.75	15.50	8.25			8.50	15.63	8.25		
	3	8.56	15.31	9.00			8.44	15.56	8.62		
	4	9.13	14.38	9.25			8.50	15.38	8.50		
	Mean	8.67	15.36	8.69			8.49	15.77	8.34		
	Standard deviation	0.368	0.769	0.515			0.030	0.500	0.275		
	Core hole meas.	8.75	15.75	8.50			8.00	16.00	8.14		
	Difference	-0.08	-0.39	+0.19			+0.49	-0.23	+0.20		
	Student's t for diff.	0.194	0.454	0.330			15.556*	0.412	0.649		

*Significant difference exists at 95 percent level.

Note: Mean overall difference = -0.054"

Table C-29. Depth of Mesh Measured by Instruments, Compared with Core Measurements

INSTRUMENT	B-1		B-2		D-1 (top)		D-2	
	t	Mean Diff.	t	Mean Diff.	t	Mean Diff.	t	Mean Diff.
Pachometer	5.951*	-0.495	7.708*	-0.962	12.657*	-1.329	11.424*	-1.412
Eddy Cur. Prox.	9.383*	-1.110	7.443*	-1.493	6.585*	-1.209	6.390*	-1.178
Resistivity	4.805*	-0.885	4.838*	-1.133	1.292	-0.384	1.698	-0.363
Resistivity					1.792	-0.631 (D-1 btm)		

*Significant at 95 percent level or higher.

Table C-30. Operator Variability in Pachometer Readings

MEASURED VARIABLE	SOURCE OF VARIANCE	DEGREES OF FREEDOM		F-RATIO	SIG. (percent)
		Num.	Denom.		
Rebar Depth	Operator	2	46	0.051	4.9
Mesh Depth	Operator	2	46	7.547	99.9
Rebar Spacing	Operator	2	38	0.352	29.4

Table C-31. Regression Analyses for Correction of Instrument Readings

Measurement	Instrument	No. of Data Points	Correlation Coef.	Critical Corr. Coef.*	Factor	Constant
Slab Thickness	Nuclear (Counter) Resistivity Ohio State gage Eddy current proximity	340 496 92 64	0.839 0.895 0.835 0.943	0.138 0.115 0.264 0.315	0.752 1.003 0.965 0.909	+2.35 +0.12 +0.36 +1.06
Rebar Depth	Pachometer Resistivity	312 148	0.961 0.870	0.146 0.210	1.936 0.943	-2.01 +0.46
Rebar Spacing	Pachometer	168	0.945	0.198	0.855	+0.99
Mesh Dep Mesh Depth	Pachometer Resistivity Eddy current proximity	192 80 64	0.622 0.821 0.935	0.185 0.283 0.315	1.002 0.668 0.784	+1.04 +2.03 +1.88

* 99 percent significance level

APPENDIX D

PHASE II FIELD STUDIES

INTRODUCTION

The field tests of Phase II were carried out on two construction projects in southcentral Pennsylvania, one in Cumberland County, on Interstate 81, and the other in Lancaster County, on route US 222. The Cumberland job had a design thickness of 9 in. and is continuously reinforced. The subbase consists of compacted crushed limestone. The Lancaster job has a design thickness of 10 in. and has wire fabric reinforcement. The subbase consists of compacted coarse gravel.

Wire fabric reinforcement is commonly used in Pennsylvania and would represent the "normal" condition. Continuously reinforced pavement is common for high volume traffic locations. In reinforced concrete slabs, used in low volume traffic locations, the bar spacing is much wider than in continuously reinforced pavements. This wider spacing may have an effect on the readings of the eddy current proximity gage (ECPG). Non-reinforced concrete is seldom used in Pennsylvania; however, it is used in other states, which may, therefore, find the ECPG of interest.

The two common thicknesses of cement concrete paving in Pennsylvania are 9 and 10 in., and these seem to represent typical thicknesses throughout the United States. It appears reasonable to expect all of the gages would operate satisfactorily over the nationwide range of pavement thicknesses if they performed properly in this test program.

Both paving projects employed slipform pavers, which are commonly used throughout the country. Although consideration was given to locating a project where forms were to be used, no such project was available during the testing period. It is felt, however, that this is not a serious omission, as nearly all future pavements throughout the United States are expected to be placed by slipform pavers.

The contractors' operations varied widely on these two projects. Although both mixed the concrete at a central plant, one had the concrete transported to the site by agitator truck, and the other had it delivered by dump trucks. The test results did not appear to be affected by these differences. On the Cumberland job, paving was done in one lift, whereas on the Lancaster job it was done in two to facilitate placement of the wire fabric. This may have had an effect on the ultrasonic readings.

The instruments evaluated were the Ohio State ultrasonic gage (OSUG), the resistivity gage, the eddy current proximity gage (ECPG), and the pachometer. After non-destructive testing had been completed, the pavements of both projects were cored at the same test locations.

FIELD PERFORMANCE OF INSTRUMENTS

Cumberland County

General

To facilitate use of the eddy current proximity gage on the Cumberland County job, 14-in.-wide strips of commercial grade (heavy duty) aluminum foil were placed on the subbase across two adjacent lanes and were permitted to extend beyond the pavement edge for identification of the sites after placement of the concrete. Fourteen strips were placed at spacings ranging from 20 to 125 ft, in a total distance of 3,745 ft of two-lane pavement. Each strip was then divided into four test sites located approximately 4, 8, 16, and 20 ft from the edge of the pavement. This yielded a total of 56 individual sites to be tested with each piece of equipment being studied. An additional 40 sites were selected randomly in either of the two lanes from areas not underlain by aluminum foil. Thus, there were a total of 96 test locations over an area of approximately 1 mile of two-lane pavement. For analysis purposes, five successive 1,000-ft sections of two-lane pavement were designated as test areas.

Testing was begun in late July 1971. It was originally thought that a moving bridge could be employed between the paving train and the finishing machine, so that testing could be attempted as soon as possible after placement of concrete. There was difficulty in obtaining readings rapidly enough with all the devices, however, such that the testing bridge was causing delays in the operations of the finishing apparatus. As a result, the bridge was deleted from the testing plans. Tests were conducted instead as soon as the concrete had reached an initial set, approximately four hours after placement. Single tests were made at each location with all the devices except the pachometer, with which duplicate tests were made. Each area was marked and numbered with spray paint for later coring.

Paving progressed at such a rapid pace that the 1-mile test section was cured to the point where it was being used as a haul road for trucks before the testing was completed, creating a safety hazard which further delayed testing. The most frequent instrumental delays were encountered with the resistivity gage, which required 15 to 20 minutes to gather all necessary data at a single test site.

Ohio State Ultrasonic Gage

Previous tests with the OSUG had been conducted by the Ohio State University personnel on test slabs during Phase I of this project. During Phase II, the gage was borrowed from the Ohio State University and operated by PennDOT personnel. Although, as before, large amounts of glycerine had to be used as a transducer-concrete surface couplant, the OSUG operated with relatively few problems, clearly indicating the interface within a very short time period. This gage can be used only after the concrete has reached an initial set.

Pachometer

The pachometer was calibrated by placing a reinforcement bar at successive 1/4-in. increments from the gage to a maximum distance of 5 in. This calibration proved nearly identical to that performed a year before, during Phase I of this project. The device again appeared to offer excellent repeatability during calibration with no noticeable temperature effects in the ambient range.

After calibration, the pachometer was easily operated throughout the testing program. No problems were encountered, even on freshly placed concrete.

Resistivity Gage

As found in Phase, I, results with the resistivity gage could be achieved only on pavement with a wet surface--either concrete which had reached an initial set or hardened concrete which was moistened with water before testing. Although readings could be obtained on fresh concrete, it was felt that such results would be somewhat unreliable due to penetration of the probes into the surface. Also, erratic

readings on fresh pavement indicated problems with electrical conduction. Without a moisture ladened surface, the device would not function properly and gave infinite resistance readings. Since each test point had to be practically surface saturated, much of the 15- to 20-minute testing time was taken up by waiting for a meaningful reading.

Another element of delay in using the resistivity gage is the time involved in interpretation of the test results by hand plotting. In an effort to solve this problem, a new technique was tried for data reduction. A computer program developed by the Soils Engineering Section of PennDOT for soil exploration studies by resistivity methods was used to reduce the raw data to appropriate curves and slope change points indicative of a material change. The computation required only 7 to 10 seconds of computer time per thickness test. This program was, therefore, used to reduce all the resistivity data to thickness values.

Eddy Current Proximity Gage

The ECPG had been calibrated in the laboratory with aluminum foil spaced over a range of 2 to 14 in. At the time it appeared to be quite sensitive and to yield repeatable readings. Phase I of this project had shown, on specially constructed test slabs, that the device was capable of detecting aluminum foil underneath parallel reinforcing bars with no noticeable effect of the steel. These bars had not been connected in any manner, however, as they were suspended by holes in the wooden slab forms. The continuous reinforcement in the pavement on the Cumberland job consisted of No.5 bars spaced 6 in. apart longitudinally. These

were laid across No.3 bars placed transverse to the pavement at approximately 30-in. intervals and supported on steel chairs. The longitudinal and transverse bars were mechanically clipped together.

The calibration of the ECPG was conducted without the insertion of bars in the space between the gage and the aluminum, since it was felt that the large 6 in. by 30 in. rectangle formed by the intersecting bars of the pavement would have no effect. Initial field data proved quite the opposite, however. The effect of the steel was so great that response to the aluminum foil on the subbase was completely obscured. It appears that, even with only parallel bars directly under the gage, a loop is established which conducts the induced signal and does not permit response to the foil. This effect discouraged further tests with the ECPG on the remaining test sites.

It is still felt that the ECPG can be used for thickness measurements of concrete in states where pavements are not reinforced. However, some modifications would have to be made, as ambient temperatures over 80° F caused the gage to produce very erratic readings.

Lancaster County

General

One hundred test locations were selected at random for a distance of approximately 1 mile of two-lane pavement. Each successive 20 tests were designated as a "test area," yielding five test areas, as for the Cumberland job. The same procedures of testing were followed as on the Cumberland project.

Ohio State Ultrasonic Gage

The OSUG operated with no problems, although the output signal was somewhat weaker than that attained on the Cumberland job. A suspicion exists that the present method of using two separate transducers spaced a known distance apart on the pavement surface may at times be inadequate, as the computed surface velocity may not be a true indication of the actual velocity through the entire mass of concrete. A more reliable value possibly could be obtained by placing one transducer on the pavement surface a few inches in from the edge and the other on the vertical sidewall prior to the placement of the shoulders.

Pachometer

The pachometer was calibrated with high repeatability on the steel fabric used as reinforcement in the pavement. Thereafter the gage operated with no problems for the duration of the project.

Resistivity Gage

The same delays and difficulties were experienced with the resistivity gage on the Lancaster job as on the Cumberland job. However, the readings appeared more stable and somewhat more rapidly attained on this project than on the Cumberland project. The reason for this difference is not known.

Eddy Current Proximity Gage

It was learned during Phase I of the study that aluminum foil placed beneath steel fabric reinforcement is indiscernible to the ECPG. Thus, foil was not placed on the subbase for thickness determinations. It was also found, however, that the gage exhibits a large

response to the presence of wire fabric. Therefore, the ECPG was calibrated by suspending samples of the same fabric used on the paving job at distances ranging from 1/2 to 6 in. beneath the gage. The response appeared repeatable and quite sensitive. The reinforcement depth was determined with the ECPG at each test location. As on the Cumberland job, instability of the readings was apparent at higher ambient temperatures.

DATA ANALYSIS

General

The analysis of the data collected for Phase II of the project was aimed toward evaluating, under field conditions, the suitability of selected instruments for determining pavement thickness or depth of reinforcement. Little conscious effort was made, from the viewpoint of experimental design, to investigate the myriad variables that influence the magnitude and variability of the measured variables. For instance, only the nominal pavement thickness (9 and 10 in.) and the type of reinforcement (fabric and bars) differed between the two paving jobs chosen in Phase II. (As it turned out, a third variable--roughness of base--was inadvertently included, as described later.)

Basically, the approach taken to evaluate the instruments used in this study was to compare their results with thickness and reinforcement depth determinations made from core specimens. Thus, it was tacitly assumed that core measurements provided "true" values. The comparisons were rendered using appropriate statistical procedures. A confidence level of 95 percent was employed throughout. Five test areas were used

from each of two paving contracts. Twenty readings were planned for each instrument on each test area. However, equipment breakdowns and other unforeseen difficulties reduced this number in some instances. The number 20 was chosen on the basis of an anticipated total (instrument plus pavement) maximum variability of 0.68 in., expressed as the standard deviation. The actual mean value, with this variability, would not be more than 1/4 in. below the sample mean more frequently than one time in 20.

Pavement Thickness Determinations

General

Two non-destructive methods of determining pavement thickness were evaluated against "standard" thickness measurements provided by coring. The test results are summarized in Table D-1 and in Figures D-1 and D-2.

Cores

Since nine individual readings were taken on each core, the core measurements provided information on the overall variability of pavement thickness as well as on the individual test site thicknesses used for comparison with the non-destructive methods. That is, the variance of the nine individual determinations on a given core was composed of the variance due to the micro-relief, or roughness, of the core bottom and the variability associated with the measuring method (including operator variance). The variance of core mean values for a given test area include, in addition, the overall variability of pavement thickness in the test area. The difference between these values, then, is the variance in pavement thickness in the test area.

Recalling that the variance is equal to the standard deviation squared, and that variances are algebraically additive,

$$\sigma_p = [\sigma_c^2 - (\bar{\sigma})^2]^{1/2}$$

where:

- σ_p = estimated standard deviation for pavement thickness in a given test area
- σ_c = standard deviation of the core mean values in a given test area
- $\bar{\sigma}$ = average standard deviation for individual core readings in a given test area

Table D-2 summarizes the variability in pavement thickness measurements by coring for the 10 test areas. Using Student's t-test with the data presented in this table, the following conclusions, significant at the 95 percent confidence level, were drawn:

1. Core bottoms on the Lancaster job were significantly rougher than those on the Cumberland job.
2. Pavement thicknesses on the Lancaster job were significantly more variable than on the Cumberland job.

The first of these conclusions was reached visually during measurement of the cores. At that time, the cores from the Lancaster job were divided into three groups, based on bottom condition, as follows:

1. bottom essentially free of base material (<25%)
2. bottom partially covered with base material (25% to 75%)
3. bottom essentially covered with base material (>75%).

The mean standard deviations of the individual readings were then computed for each of the above groups. Finally, these mean values were compared using Student's t-test, and the mean of group 3 was found to be significantly greater than that of either group 1 or group 2. There was no significant difference between groups 1 and 2. This indicates that the higher within-core variance on the Lancaster job is attributable to inclusion of base material in the bottom of the core. These results are summarized on Table D-3.

Further evidence of the greater variabilities encountered on the Lancaster job was found in determining the number of cores required to provide a mean determination of pavement thickness that is no more than 1/4 in. greater than the actual mean thickness at the 95 percent confidence level. Table D-4 shows the number of test determinations needed to satisfy the above criteria, based on the standard deviations of the measured values. It can be seen from this table that, for the Cumberland job, only 1 or 2 cores were needed per 1,000 lane-ft, whereas the Lancaster job required from 2 to 6 cores for the same-size test section. All of these values are, however, far below the actual number of cores taken, which ranged from 16 to 20, as shown on the table.

The reproducibility of the core measuring technique was checked by making duplicate determinations on nine cores with two different operators. The differences between the mean values of the two operators were checked for significance (at the 95 percent level) by means of Student's t-test. The results are shown in Table D-5. It can be seen that a significant difference existed for only one of the nine cores, and even in this case the mean values differed by only 0.04 in. The significance of the difference stems from the very low pooled variance for the two operators. Thus, it is concluded that operator variability has no effect on the variance of core determinations. The core measuring apparatus is shown in Figure D-3.

Ohio State Ultrasonic Gage

The Ohio State ultrasonic gage gave results that were much closer to the core thickness determinations than did the resistivity method, both in magnitude and variance. This can be seen in Table D-1 and in Figures D-1 and D-2. Curiously, however, the OSUG did not indicate a significantly greater variability for the Lancaster job than for the Cumberland job, as had the cores. A possible explanation is that the OSUG averages the thickness over a larger area.

Another unusual observation was that the thickness determinations by the OSUG averaged 0.16 in. larger than the cores from the Cumberland job, and 0.52 in. smaller than the cores from the Lancaster job. This fact precludes using a universal calibration equation for converting OSUG determinations to thickness. Rather, it appears that a calibration relationship would have to be established for each job and checked periodically by means of coring. While the reasons for this anomaly were not clearly identified, it appears that inaccuracies in determining the pulse velocities may be the major contributing factor. The base condition may also be significant. (While the base condition did not appear to be a factor in terms of variability of the OSUG, this does not preclude its having a significant influence on the magnitude of the determined thickness.) A third explanation may lie in the possible plane of discontinuity in the pavement of the Lancaster job, due to the two lifts used in concrete placement.

The low within-test-area variance exhibited by the OSUG was favorably surprising. The magnitude of the variance is significantly lower for these tests, which were conducted under actual job conditions, than it was in the Phase I experiments. However, it will be recalled that the earlier

tests incorporated a significantly larger number of pavement variables. Further evidence of the low variability is the need for only five or fewer determinations per 1,000 lane-ft test site (except for one case, which required nine) to give an average value that was no more than 1/4 in. greater than the actual value, at the 95 percent confidence level (Table D-4).

Resistivity Gage

As shown on Table D-1 and in Figures D-1 and D-2, the results of pavement thickness measurement by the resistivity method were highly disappointing. Figures D-1 and D-2 are especially illustrative in showing the wide variation of the results as compared with those from cores. This is also illustrated on Table D-4, which reveals that at least 15 determinations would be required per test area to provide a mean value no more than 1/4 in. greater than the average value, and that the average number of tests required would be about 40 per test area. Furthermore, there are large discrepancies between the magnitudes of the measured thicknesses and the core values, with the resistivity being on the low side. However, because of the large variabilities of the resistivity determinations, the differences between mean values for resistivity and core measurements in the test areas are frequently not statistically significant.

It was thought that perhaps the large variance associated with the resistivity method was related to difficulties in interpreting the inflection points in the data plots from which thickness values are determined. However, a comparison among three operators, who interpreted the same data from 10 tests, revealed no significant difference at the 95 percent confidence level (Table D-6). One of the operators

did differ significantly from the other two at the 90 percent level. These results seem to indicate that the method is inherently highly variable.

Pulse-Echo Ultrasonic Gage

This preliminary evaluation of the pulse-echo ultrasonic gage (PEUG) is based on data supplied by the Maryland State Roads Commission.

Figure D-4 shows calibration data for core lengths plotted against PEUG readings. A very high correlation exists between these results and the core thicknesses for the data shown here ($r = 0.918$). However, this correlation is misleading, because what is actually shown on Figure D-4 are two univariant populations. Consequently, the analysis in this case virtually involves a correlation between two points which, of course, produces an almost perfect correlation. The correlations within each grouping of points, however, are not significant.

Figure D-5 compares frequency distributions of the PEUG readings on actual paving jobs with core length determinations at the same locations. While the core lengths (i.e., the actual pavement thicknesses) covered a fairly wide range of about 8.8 to 10.4 in., the PEUG thickness measurements gave fairly constant results at about 9.1 in. The correlation coefficient between the cores and the gage readings here was 0.108, which is not significant. It appears that the PEUG lacks the sensitivity required to produce acceptable results at this stage of its development.

Inspector's Probe

Probe depth determinations of pavement thickness by PennDOT inspectors during the paving operations were examined and compared with core and instrument determinations. These probe depths, while covering the same portions of the paving projects as the test sections, were not performed at precisely the same sites as the test determinations.

Comparison of probe depths with core thickness measurements on Figures D-1 and D-2 reveal two interesting facts:

1. The probe depth frequencies peak very sharply at precisely the design thicknesses (9 and 10 in.), while core thicknesses peak at 0.3 and 0.4 in. greater than the design thickness.
2. The variance of the probe depths is very small in comparison with the core measurements. However, the probe depth variance is greater for the Lancaster job than for the Cumberland job, as was the case with the core variances.

These results cast considerable doubt on the validity of probe measurements of plastic concrete to determine pavement slab thickness.

It is very difficult to gage slab thickness with a probe due to the interference of aggregate particles and the uncertainty of contact with the base. In all likelihood, probe measurements that reach or exceed the design value are generally reported as the design value because of the latter of these two difficulties. Probe depths that stop short of the design value are most likely repeated until a satisfactory result is obtained, because of the inspector's inability to determine whether he has truly gaged the depth or is experiencing interference from aggregate particles.

Reinforcement Depth Determinations

General

Three non-destructive methods of determining reinforcement depth were evaluated against "standard" depth measurements provided by coring. The test results are summarized in Table D-7 and in Figures D-6 and D-7.

Cores

The variances in reinforcement depth very obviously differed with reinforcement type (Table D-7). The Cumberland job showed standard deviations within the test areas of 0.109 to 0.211 in., whereas the Lancaster job had values that varied between 0.405 to 0.553 in. This is not unexpected--it would be anticipated that the position of mesh (Lancaster job) would be considerably more difficult to control than that of bars. This point is also illustrated in Table D-4, where it can be seen that bar position can be determined to the precision criteria previously prescribed with only one or two cores per 1,000 lane-ft. Mesh depth, however, requires 8 to 14 cores. The greater spread of the reinforcement depth from core data in the Lancaster job is also shown by comparison of Figures D-6 and D-7.

Pachometer

The pachometer provided reinforcement depth determinations for both bars and mesh that compared exceedingly well with the core determinations both in magnitude and in variance. This observation is confirmed in Tables D-4 and D-7, and in Figures D-6 and D-7. In addition, very high correlations were found to exist for individual pachometer determinations versus core measurements (significant at better than the 99.9 percent level for both the Cumberland and the Lancaster jobs). Also, it should be noted from Tables D-4 and D-7 that the pachometer reveals--as did the cores--that the mesh depth determinations are considerably more variable than those of the bars.

Resistivity Gage

The resistivity method proved to be as ineffective in accurately determining reinforcement depth as it was for pavement thickness. The

results showed very high variability, and the average values did not compare well with core determinations. These points are well illustrated in Table D-7 and in Figures D-5 and D-7. The wide variances encountered are further illustrated in Table D-4, which shows that more than 20 tests are usually required to give an average value meeting the precision criteria previously established.

Eddy Current Proximity Gage

The ability of the eddy current proximity gage (ECPG) to determine the depth of reinforcing bars was exceedingly poor, as shown by Tables D-4 and D-7 and especially in Figure D-6. The standard deviation is nearly 2 in., and the magnitudes of the determined depth bear little similarity to the actual reinforcement depths.

However, for mesh, the ECPG provided results that compared reasonably well with core measurements (Tables D-4 and D-7, and Figure D-7). The variances encountered are only slightly greater, on the average, than those for the core and pachometer determinations. The magnitudes of the depth determinations, however, do not compare nearly as well with cores as do the pachometer readings, although the correlation between mesh depth by cores and by the ECPG is still significant at better than the 99.9 percent level.

DISCUSSION AND CONCLUSIONS

Comments were solicited from engineering personnel of the Construction Bureau of PennDOT, who had witnessed the research, as well as from the engineers who were in charge of the two paving jobs. Both of these engineers stressed that the pachometer and the OSUG operated satisfactorily, but they were of the opinion that the OSUG was rather

unwieldy in size. They also felt that testing device manufacturers should pay more attention to the development of a gage which would operate in conjunction with the paver to control concrete depth during placement.

The following conclusions were drawn with respect to the usefulness of the test devices under field conditions:

1. The system with the most promise for measuring concrete pavement thickness is the Ohio State ultrasonic gage (OSUG). A man can be trained to operate the system and obtain reliable results within a few days. Thereafter, a complete test can be run in a few minutes. Concrete must have attained initial set to obtain reliable results.
2. The pachometer, as also shown in Phase I of this research, provided reliable and extremely rapid readings of reinforcement depth after proper calibration. Although the instrument is insensitive to steel below a depth of 5 in., this creates no problem in testing on highways since reinforcement is normally placed from 2 to 4 in. below the surface. If care is taken, the device can be used on freshly placed concrete, with the results totally reproducible on the hardened concrete.
3. The resistivity gage proved too time-consuming for further serious consideration. Data were reliable only when the concrete surface was saturated, a condition difficult to maintain uniformly, particularly on hot windy days. Initial data reduction is still a problem. Ten sets of data were reduced separately by two men and by the computer program discussed earlier. It was found that three such separate reductions can yield three different answers for thickness, varying by as much as an inch.

D-19

4. The eddy current proximity gage (ECPG) cannot be used to measure the thickness of reinforced concrete, due to the pronounced effect of steel on the instrument. The device may still have some promise for states placing plain cement concrete pavements. Large variations with temperature were observed, however. As the ECPG proved to be the most rapid reading of any of the devices studied, it could possibly be incorporated into a paver to control thickness of non-reinforced concrete if a solution can be found to the temperature problem. After proper calibration, the ECPG can be used for detection of steel fabric depth. However, it cannot reliably detect parallel deformed bars when these are connected to transverse bars spaced as closely as 2 ft apart.

D-20

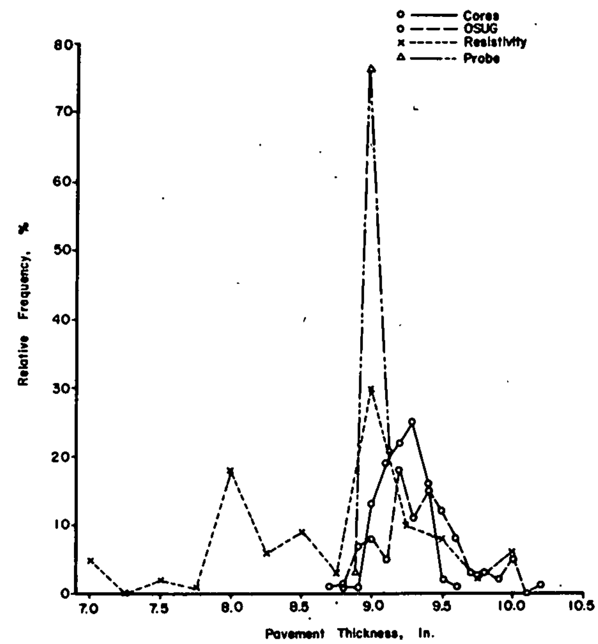

Figure D-1. Results of non-destructive testing and coring for pavement thickness on the Cumberland job.

D-21

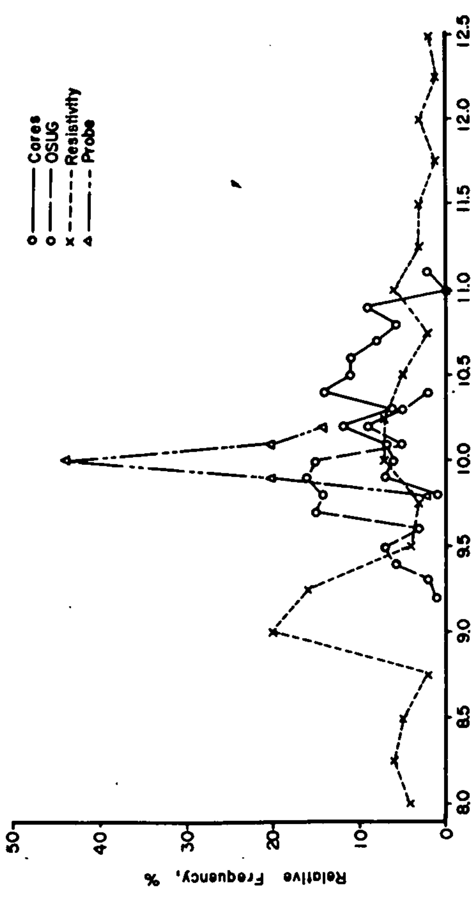

Figure D-2. Results of non-destructive testing and coring for pavement thickness on the Lancaster job.

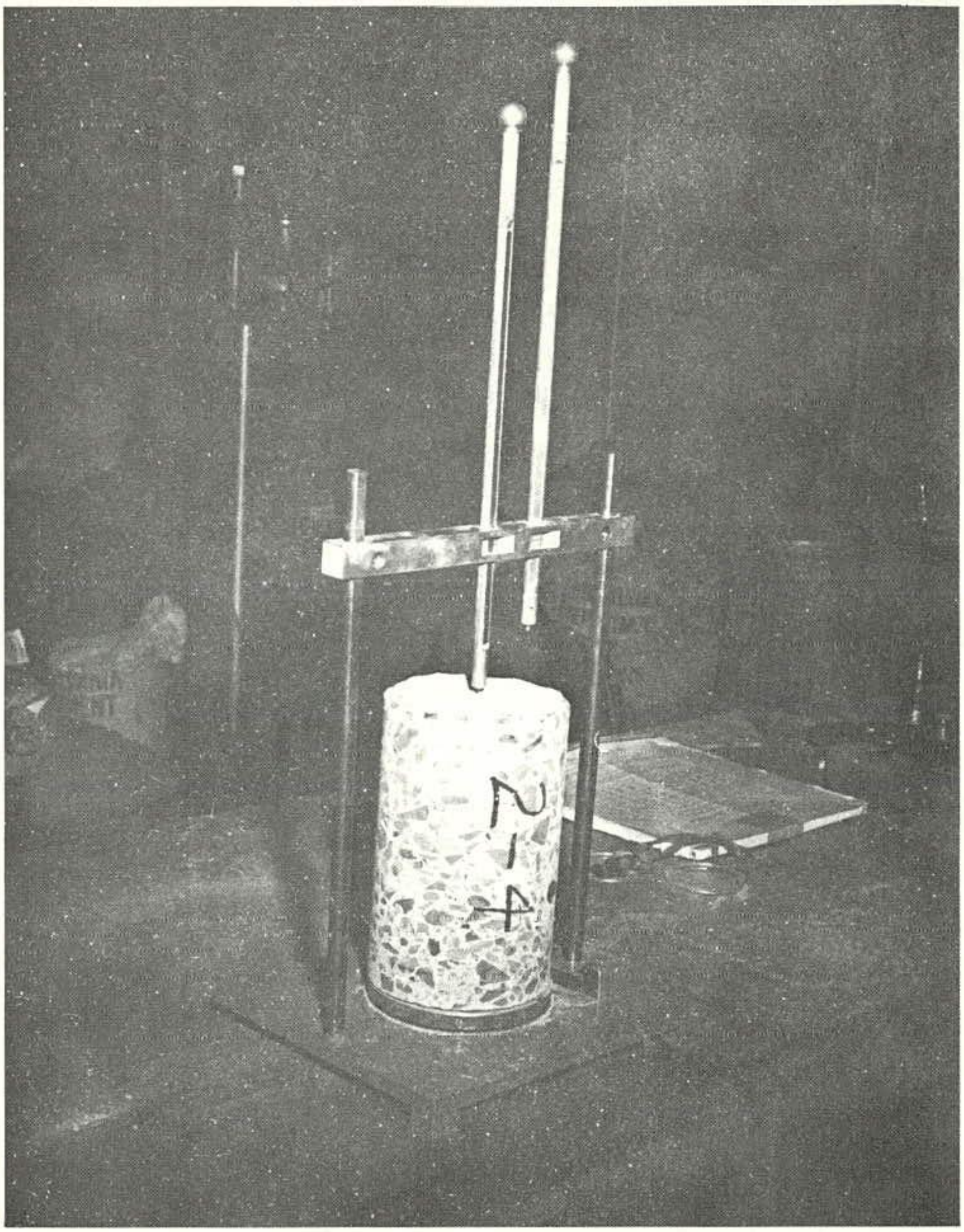

Figure D-3. Core measuring apparatus.

D-23

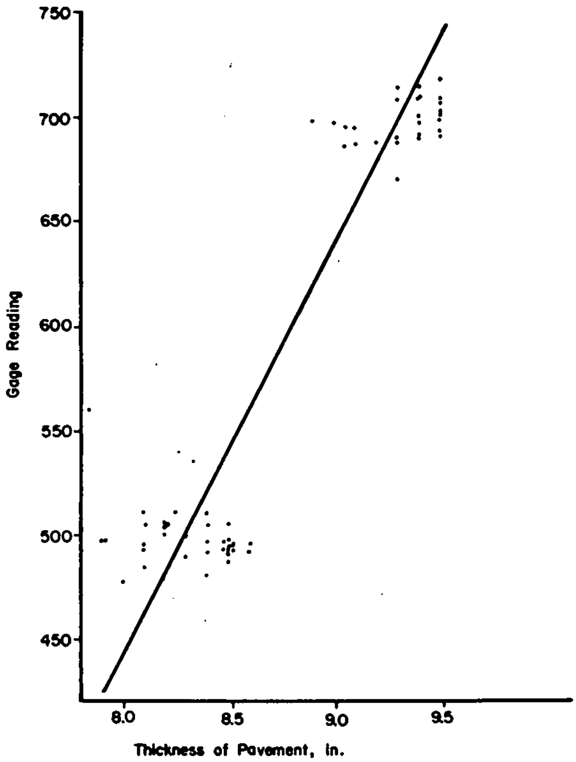

Figure D-4. Pulse-echo ultrasonic gage readings compared with core lengths.

D-24

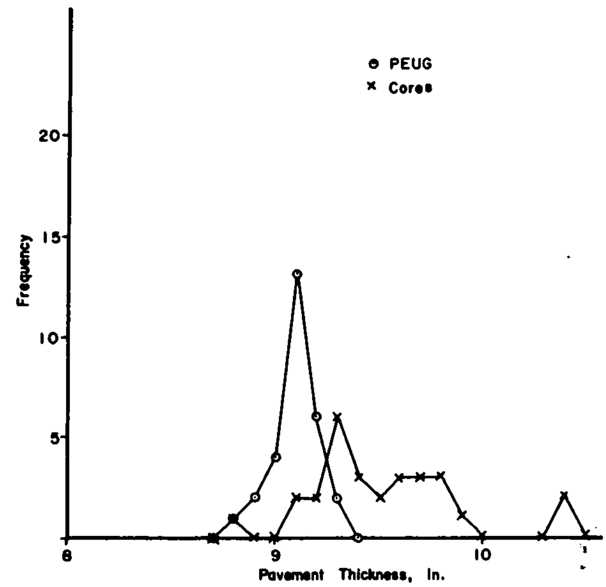

Figure D-5. Comparison of pulse-echo ultrasonic gage readings for pavement thickness with core lengths. (Data obtained from the Maryland State Roads Commission.)

D-25

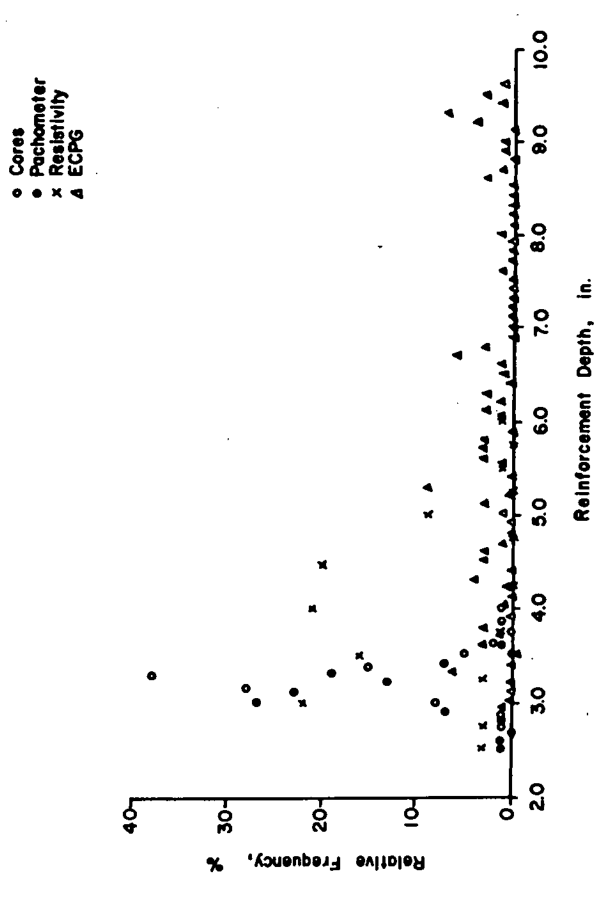

Figure D-6. Reinforcement depth determinations, Cumberland job.

D-26

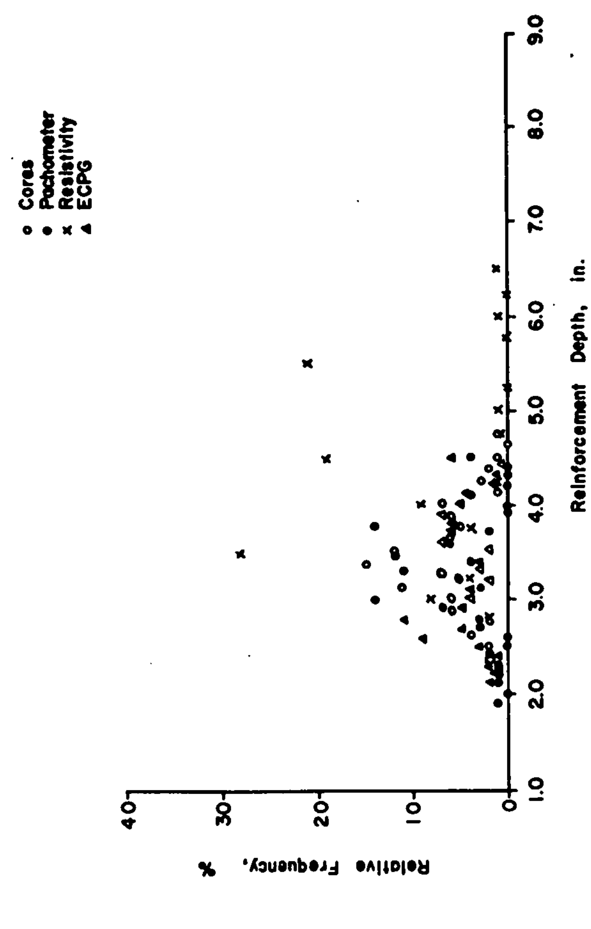

Figure D-7. Reinforcement depth determinations, Lancaster job.

Table D-1. Summary of Pavement Thickness Determinations

JOB	AREA	CORE No.	CORE Avg	CORE S.D.	RESISTIVITY No.	RESISTIVITY Avg	RESISTIVITY S.D.	OSUG No.	OSUG Avg	OSUG S.D.
CUM[a]	I	16	9.21	0.167	16	8.62	0.801	16	9.41	0.439
	II	20	9.21	0.107	19	8.45	0.898	19	9.46	0.258
	III	20	9.24	0.122	17	8.82	0.589	20	9.27	0.257
	IV	20	9.32	0.120	20	8.88	0.651	18	9.46	0.251
	V	20	9.31	0.182	18	8.73	0.660	No tests		
LAN[b]	I	20	10.47	0.348	20	9.10	0.714	20	9.93	0.212
	II	20	10.65	0.273	20	9.85	1.024	20	9.84	0.268
	III	20	10.39	0.216	20	9.91	1.173	20	9.83	0.315
	IV	20	10.22	0.289	20	9.88	1.213	20	9.81	0.236
	V	20	10.59	0.208	20	9.73	1.369	20	10.02	0.224

[a]Bar reinforcement
[b]Mesh reinforcement

Table D-2. Variability in Pavement Thickness Measurements by Coring

JOB	TEST AREA	No. of Cores	Mean Core S.D., σ	S.D. of Core Lengths, σ_c	Estimated True S.D. of Pavement, σ_p
CUM	I	16	0.054	0.167	0.158
	II	20	0.049	0.107	0.095
	III	20	0.061	0.122	0.106
	IV	20	0.060	0.120	0.104
	V	20	0.058	0.182	0.173
LAN	I	20	0.071	0.348	0.341
	II	20	0.075	0.273	0.262
	III	20	0.067	0.216	0.205
	IV	20	0.068	0.289	0.281
	V	20	0.072	0.208	0.195

Table D-3. Effect of Core Bottom Condition on the Variance of Core Length Measurement (Lancaster Job)

Column Number	1	2	3	1 vs. 2	2 vs. 3	3 vs. 1
Number of Cores	47	42	11			
Core Bottom Condition	25% covered with base material	25-75% covered with base material	75% covered with base material			
S.D. of Length Measured Average S.D. of Average	 0.064 0.023	 0.068 0.023	 0.107 0.048			
Student's t-Test d.f. t				 87 0.810	 51 3.771*	 56 4.228*

*Significant at the 99 percent level.

Table D-4. Number of Tests Made and Required to Determine Pavement Thickness and Reinforcement Depth

JOB	AREA	Pavement Thickness: Core Taken	Core Needed	Resistivity Taken	Resistivity Needed	OSUG Taken	OSUG Needed	Reinforcement Depth: Core Taken	Core Needed	Resistivity Taken	Resistivity Needed	Pachometer Taken	Pachometer Needed	ECPG Taken	ECPG Needed
CUM[a]	I	16	2	16	28	16	9	16	2	16	16	16	2	16	52
	II	20	1	19	35	19	3	20	1	19	20	20	1	20	216
	III	20	1	17	15	20	3	20	1	17	25	20	1	20	150
	IV	20	1	20	19	18	3	20	2	20	26	20	2	14	207
	V	20	2	18	20	No tests		20	2	18	13	20	3	No tests	
LAN[b]	I	20	6	20	23	20	2	20	12	19	37	20	10	20	20
	II	20	4	20	46	20	4	20	11	20	9	20	15	20	12
	III	20	3	20	60	20	5	20	8	20	56	20	13	20	9
	IV	20	4	20	64	20	3	20	11	20	24	20	10	20	12
	V	20	2	20	82	20	3	20	14	20	29	20	10	20	21

[a]Bar reinforcement
[b]Mesh reinforcement

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Table D-5. Results of Reproducibility Test of the Core Measuring Method

Core No.	Operator 1 No.	Operator 1 Avg	Operator 1 S.D.	Operator 2 No.	Operator 2 Avg	Operator 2 S.D.	t*
I- 2	9	9.33	0.054	9	9.31	0.141	0.400
I- 4	9	9.47	0.102	9	9.45	0.113	0.396
I- 6	9	9.33	0.039	9	9.33	0.024	0.000
I- 7	9	9.25	0.064	9	9.24	0.012	0.286
I- 8	9	9.46	0.038	9	9.47	0.041	0.549
I- 9	9	9.06	0.049	9	9.05	0.042	0.476
I-12	9	9.22	0.031	9	9.23	0.048	0.549
I-13	9	9.04	0.027	9	9.00	0.029	3.226
II- 4	9	9.11	0.017	9	9.11	0.043	0.000

*Critical value = 1.746 (at the 95 percent significance level.

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Table D-6. Results of Reproducibility Test of the Resistivity Method

TEST NO.	OPERATOR NUMBER 1 (Resistivity)	2 (Resistivity)	3 (Resistivity)	1-2 (Sign Test)	1-3 (Sign Test)	2-3 (Sign Test)
101	9.0	10.0	8.8	-	+	+
102	9.0	10.4	10.5	-	-	-
103	8.5	10.0	9.0	-	-	+
104	8.0	10.4	10.5	-	-	-
105	9.5	9.5	9.5	0	0	0
106	9.0	9.5	9.5	-	-	0
107	8.0	10.0	10.0	-	-	0
108	9.0	9.0	9.0	0	0	0
109	8.0	8.7	8.4	-	-	+
110	9.5	9.0	10.0	+	-	-
Number +				1	1	3
Number -				7	7	3
Number + and -				8	8	6
Critical number + or - (95%)				0	0	0
Critical number + or - (90%)				1	1	0
Significant at 95%?				no	no	no
Significant at 90%?				yes	yes	no

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Table D-7. Summary of Reinforcement Depth Determinations

JOB	AREA	CORE No.	CORE Avg	CORE S.D.	RESISTIVITY No.	RESISTIVITY Avg	RESISTIVITY S.D.	PACHOMETER No.	PACHOMETER Avg	PACHOMETER S.D.	ECPG No.	ECPG Avg	ECPG S.D.
CUM[a]	I	16	3.19	0.176	16	3.37	0.592	16	3.14	0.182	16	4.68	1.089
	II	20	3.23	0.109	19	3.66	0.663	20	3.10	0.130	20	6.49	2.226
	III	20	3.28	0.112	17	4.26	0.752	20	3.20	0.126	20	6.96	1.856
	IV	20	3.21	0.211	20	3.55	0.772	20	3.09	0.180	14	6.16	2.183
	V	20	3.13	0.173	18	4.28	0.548	20	3.03	0.236	No tests		
LAN[b]	I	20	3.34	0.511	19	3.96	0.918	20	3.29	0.472	20	3.30	0.663
	II	20	3.44	0.499	20	3.65	0.432	20	3.27	0.575	20	3.81	0.515
	III	20	3.34	0.405	20	4.15	1.131	20	3.27	0.529	20	3.62	0.436
	IV	20	3.23	0.495	20	4.80	0.733	20	3.27	0.472	20	2.88	0.522
	V	20	3.49	0.553	20	4.36	0.817	20	3.40	0.465	20	3.33	0.695

[a]Bar reinforcement
[b]Mesh reinforcement

APPENDIX E

DEVELOPMENT OF ACCEPTANCE SPECIFICATIONS

INTRODUCTION

A survey was made of most state specifications in an attempt to determine which criteria are presently applied to pavement thickness acceptance utilizing coring techniques. A tabulation of many of the state requirements is shown in Table E-1. It is apparent that the most frequent sampling procedure used is a minimum of one core to represent one lane, 1,000 ft in length. In most cases, if the average height of this core is within -0.20 in. of the design thickness, the pavement is accepted with 100 percent payment to the contractor. Larger deficiencies are usually scaled to reflect degrees of penalty to the contractor with deficiencies greater than 0.5 in. overall requiring pavement removal, although several states allow a pavement to be 0.5 in. below specification and still guarantee 100 percent payment.

It is not apparent how the various testing and acceptance criteria evolved, since thev have little basis in logical sampling techniques. In this project, it was found that the mean standard deviation for pavement thickness, as measured from cores, was independent of pavement design thickness and was approximately 0.3 in. Thus, the observed thickness at a point in the pavement may be as much as 0.6 in. greater than the actual average thickness, at the 95 percent confidence level. With the standard deviation of 0.3 in., approximately seven cores are needed to guarantee that the true mean thickness is no more than 0.2 in. less than the sample mean at a 95 percent confidence level. Most states,

however, rely on the minimum of one core per 1,000 lane-ft rather than the minimum number predicted by sampling theory.The destructive nature

the minimum number predicted by sampling theory. The destructive nature

of coring, along with the large amount of testing required within a limited time period, is probably responsible for the reluctance to core. The exercise of numerous controls during the construction aimed at attaining design thickness as a minimum evidently has been accepted as the preferable alternative. Non-destructive testing, however, which is more rapid and economical, can be used to significantly increase the number of thickness tests without injury to the pavement and without increasing the over-all testing budget significantly.

SAMPLE SIZE DETERMINATIONS - PHASE II FIELD STUDIES

General

A major difficulty in acceptance standards based on statistical concepts is the selection, or even identification, of the population under investigation. In the case of measurements on portland cement concrete pavements, several statistical population generations are encountered. In order of decreasing hierarchy, the several population generations are:

1. All concrete pavements in the country of a given design thickness
2. The pavements of a given design thickness constructed to a given set of specifications (most likely in terms of a given state within a specific time period)
3. Pavement constructed on a given continuous highway section or a particular paving contract by a particular contractor
4. Pavement constructed by one contractor on a given section of highway during a specified time interval (e.g., one day of

paving operations), or a specified quantity of paving (e.g., 1,000 lane-ft).

The choice of the population to be represented by the computed sample size is obviously either item 3 or 4 in the above listing, since the acceptance standard relates to evaluation of contractural performance by a specific contractor on a given contract.

In deference to custom, and because it represents the conservative point of view with respect to quality assurance, the population represented by item 4 was selected for the testing done as part of the Phase II field studies.

Procedure

As described in Appendix D, 16 to 20 determinations were made for each instrument and coring per 1,000 lane-ft test section. Using standa deviations computed from these readings, required sample sizes were computed to provide a measure of the consistency of the readings for the various instruments, as follows:

$$\pm t = 1.645\sigma / n^{1/2} \qquad \text{or} \qquad n = (1.645\sigma/\pm t)^2$$

where:

$\pm t$ = accuracy desired for overall measurement

σ = mean test method standard deviation

n = number of tests

This relationship determines the number of tests required for a particular instrument to yield a 95 percent confidence interval for the sample mean of $\pm t$. With -0.25 in. being the tolerance allowed by most states for full contract payment, this is further reduced to

$$n = 43.4\sigma^2$$

The number of determinations needed for each instrument, as presented in Table D-4 of Appendix D, is based on this equation.

ACCEPTANCE SPECIFICATIONS

Introduction

The technique described in the previous section is sufficient for the comparison of the utility of different instruments, but it is of little use to the highway engineer who needs to know whether or not the measured variable (thickness or reinforcement location), per se, meets prescribed standards. Consequently, a set of procedures was developed for use in acceptance of pavements. The proposed new test methods are based on rational tolerances and probability levels and are related to design values, rather than simple mean values.

It was deemed appropriate to make a review of current specifications and test methods, construction practices to which these are applied, and proposed new approaches to specification and testing methods. As a result of these studies, and the work done in Phase II of this project (see Appendix D), tentative approaches to the desired results were developed. Instead of one set of specifications and a single test method, several possible solutions are presented. The reasons for each are supplied, along with its advantages and disadvantages.

General

A highway specification is a means of providing the traveling public with an adequate and economical roadway upon which vehicles can move easily and safely from point to point. These specifications should be simple and clear, so that both the contractor and the contracting agency understand what is expected.

As stated by NCHRP:

> A realistic specification is one that recognizes that there is a cost associated with every specified limit and that the characteristics of all materials, products, and construction are inherently variable. It is certainly unrealistic to set an unnecessarily restrictive limit and then require that all measurements and observations conform to it precisely (130, p. 4).

Moreover, the type of men using the specifications in construction should also be considered. If the specifications are too complex for these men to understand, an inferior product can easily result.

It is felt that an "end result" type of specification should be used. This will provide the contractor with the greatest freedom of operation while assuring that the desired quality of pavement will be constructed.

Pavement Thickness

The following is a review of present practices, with comments and recommendations:

Lot Size.--The present common practice is to use a lot size of 1,000 lane-ft. This appears to be based upon the use of forms in paving operations. In view of present-day rapid paving operations, a lot size of either 1/2 lane-mi. or 1 lane-mi. would be more realistic. The lot size should represent about 1 to 2 hours normal operation by the contractor, using current batch control, transit equipment, and placing equipment.

Number of Samples.--The present practice often is for one sample to represent a lot, unless this sample fails to pass, in which case additional samples are obtained. It is unrealistic to expect all samples to meet a given design thickness, in fact ignoring the variability of construction operations and measuring techniques. The

use of a minimum number of tests is proposed to represent a lot, with the number to be based on normally expected variations.

Location of Deficient Areas.--The present practice is to locate deficient areas. However, with limited sampling, how many such areas will be located? It would seem realistic to accept a lot on the basis of an average thickness value.

Size of Deficient Areas.--The present practice is to attempt to define the size of deficient areas by additional coring. In the proposed specifications, this will be replaced by the use of the average thickness within a lot. A lower limit will be placed on all cores, for example, 1/2 in. short of design thickness, for acceptance of a lot. All acceptance, penalty, or rejection will apply to the entire lot.

Timing of Measurements.--The present use of coring requires that the measurements are, by necessity, after the fact. Non-destructive testing should make it possible to accept or reject pavement thickness within a single day. This will enable the contractor to regulate his own operations and should provide an increase in the efficiency of the overall operations.

Tolerances.--In the design of pavement thickness, a tolerance is allowed for factors such as normal variation in construction operations, variations in the measurement technique, wear of the pavement during its expected lifetime, and loss of support. In other words, the design engineer will specify an extra thickness of pavement to allow for these variations.

Earlier in this appendix it was indicated that most states accept either an 0.20 or 0.25 in. tolerance for 100 percent payment. The corresponding reduction in expected number of load applications is 11 to 13 percent for a 9-in. slab (131). The project personnel were unable to locate information on what extra thickness is allowed in pavement design

to account for the factors just mentioned, but it may be assumed that it is greater than 0.25 in. It is proposed to use 0.5 in. as the maximum deficiency allowable for any one test result.

Number of Tests.--In order that the specification be clear and easily understood, it is proposed to reduce all statistics to simple fixed numbers. These would represent what would be expected on a paving job with large variability in pavement thickness. It is proposed to use a fixed number of tests per lot. Acceptance will be based upon the average of these tests and a maximum allowable number of test values below the design value.

Acceptance Criteria.--At the present time a pavement may be accepted, accepted with penalty, or rejected. The criteria for these categories vary from state to state, and it is felt that the exact limits are a prerogative of each state. However, for the purposes of this study, the following limits are proposed: acceptance--design thickness or greater; penalty--thickness within -0.01 and -0.50 in. of design thickness; rejection--thickness less than -0.50 in. of design thickness.

Basis of Penalty.--The bases for penalties vary widely from state to state. Three possible methods are: 1) based on reduction of yardage of concrete placed (percentage of design thickness), 2) based on area deficient in thickness (number of tests per lot deficient), and 3) based on reduction in expected number of load applications (131).

Assuming satisfactory work is being obtained from present practices, the proposed specifications should result in about the same or a slight improvement in the quality of workmanship as at present. The proposed acceptance sampling plans, shown on Figures E-1 and E-2, are similar in principle to methods proposed in a recent report of the New York

Department of Transfortation (132). The area concept has also been mentioned previously in the literature in conjunction with quality control in the highway field (133).

The following specifications were proposed for use in Phase III of this study, with penalties applied as just discussed under "Basis of Penalty."

Alternative Specification I

1. The lot size must be either one half (1/2) lane-mi. or one (1) lane-mi. of finished concrete pavement (see "Lot Size" above).
2. There must be six (6) tests conducted at random locations within the lot.
3. If the average of the six (6) tests is greater than the design thickness and not more than one (1) test falls below the design thickness, accept the lot.
4. If the average of the six (6) tests is above the design thickness minus one half (1/2) in. and not more than one (1) test falls below the design thickness minus one half (1/2) in., apply penalties as shown in Table E-2 (or E-3, or E-4) based on the average of the six (6) tests.
5. If two (2) or more tests, or the average of the six (6) tests are below the design thickness minus one-half (1/2) in., reject the lot.

Alternative Specification II

1. The lot size must be either one half (1/2) lane-mi. or one (1) lane-mi. of finished concrete pavement.
2. There must be five (5) tests conducted at random locations within the lot.

3. If the average of the five (5) tests is greater than the design thickness and not more than one (1) test falls below the design thickness, accept the lot.

4. If the average of the five (5) tests or two (2) or more tests falls below the design thickness minus one half (1/2) in., reject the entire lot.

5. For all situations not covered by items 3 or 4, obtain five (5) additional tests at random locations within the lot.

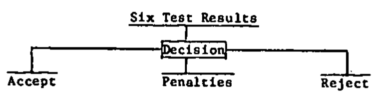
6. If the average of the ten (10) tests is greater than the design thickness and not more than three (3) tests fall below the design thickness, accept the lot.

7. If the average of the ten (10) tests, or two or more tests, is below the design thickness minus one half (1/2) in., reject the entire lot.

8. For all situations not covered by items 6 or 7, apply penalties as indicated in Table E-2 (or E-3, or E-4).

Discussion of Alternative Specifications for Pavement Thickness

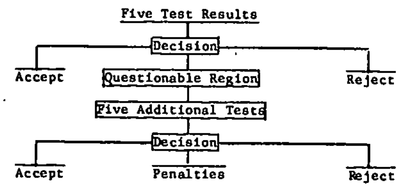
Alternative Specification I is based on a simple one-decision principle:



This is the simplest field form available. The use of six tests will result in a confidence level of greater than 95 percent in the decision

being correct, if the standard deviation of the pavement thickness is not greater than 0.25 in. and the mean value is equal to the design thickness.

Alternative Specification II is based on a two-decision principle:



This method has a greater probability of being correct over Alternate Specification I. It may, however, increase the work required in the field. The reduction in the number of tests used in the first decision will bias the decision in favor of accepting lots that may not be accepted in Alternative Specification I, slightly increasing the risk to the state. However, use of the 10 tests in the second decision will increase the probability of being correct, reducing the risk of a wrong decision to both the contractor and the state.

Reinforcement

The testing equipment currently available is not able to locate reinforcement at depths greater than 5 in. For this reason, it is proposed to use the equipment only to determine if sufficient cover exists. As this is an important item in the placement of steel, it is felt that it should be used to control operations directly behind the striking-off operations. This will enable corrections to be conducted during placement.

The following procedure was followed during Phase III of this study:

1. Measure the depth of steel at two random locations between the striking-off and the finishing operations for each 100 ft of pavement placed.
2. If any tests indicate that the reinforcement is less than design depth minus 1/2 in., paving operations must cease until corrective action is taken. The allowable steel depth greater than design depth should be considered by the states independently.

The mobility and accuracy of the pachometer makes the rapid checking of steel depth possible. The use of two tests for a small lot size of 100 ft of pavement will result in over 95 percent confidence that sufficient cover exists at all locations. Measuring the depth of reinforcement prior to finishing operations will not alter the results, as finishing is principally to ensure a plane surface and provide a proper texture to the surface. Measurements performed directly behind the striking-off operations will limit the amount of reinforcement with insufficient cover.

SPECIFICATIONS FOR TEST METHODS

Two test methods are proposed, one for acceptance of pavement thickness and one for determination of depth of reinforcement. The test method for pavement thickness is proposed for both alternatives presented in the specifications.

Test Method for Pavement Thickness Acceptance

1. Scope

1.1 This method covers procedures for determining the thickness of portland cement concrete pavement utilizing non-destructive test methods and instruments.

2. Apparatus

2.1 Non-destructive apparatus employed for thickness testing of portland cement concrete pavement must have been proven capable of determining pavement thickness within a standard deviation of three tenths (0.3) in.

2.2 The apparatus must be capable of measuring concrete pavement thickness over a range of four (4) to twelve (12) in. within two (2) hours of concrete placement.

2.3 The apparatus must have been proven stable and its results repeatable within one tenth (0.1) in. over the temperature range of 40° to 120° F.

2.4 The apparatus must have its operation checked on each project by one of the following methods:

2.4.1 Correlation with Cores

2.4.1.a Conduct five (5) tests on the first one half (1/2) mi. of pavement placed by the contractor, marking each location with paint or some other method.

2.4.1.b The next day, obtain cores at each test location and measure their length as described in ASTM Specification C174-49.

2.4.1.c Determine at each location the difference between the non-destructive test thickness and the measured core thickness.

2.4.1.d Average the results in 2.4.1.c and apply as a correction to all future non-destructive test results on the project.

2.4.1.e If mix design, cement, or aggregate changes occur, repeat 2.4.1.a through 2.4.1.d to establish a new correction.

2.4.2 Correlation with Prepared Test Blocks

2.4.2.a Select an area near the start of paving where the base will be the same as will exist under the completed pavement. This

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area should be three (3) by seven (7) ft in size, plane to one tenth (0.1) in.

2.4.2.b Construct a form containing three (3) two (2) ft sq steps: design thickness minus one half (1/2) in., design thickness, and design thickness plus one half (1/2) in.

2.4.2.c At the start of paving operations, fill the form with the same concrete being used in the paving operations. Compact the concrete by vibration or rodding and strike off a plane surface.

2.4.2.d After two (2) or more hours, conduct two (2) or more non-destructive tests on each step.

2.4.2.e Determine, for each step, the difference between the non-destructive test thickness and the step thickness.

2.4.2.f Average the results in 2.4.2.e and apply as a correction to all subsequent non-destructive test results on the project.

2.4.2.g If mix design, cement, or aggregate changes occur, repeat 2.4.2.a through 2.4.2.f to establish a new correction.

3. Procedure

3.1 Turn on the test apparatus and allow to warm up for at least five (5) minutes.

3.2 Select the lot size at either one half (1/2) lane-mi. or one (1) lane-mi.

3.3 Select six (6) test sites in a random manner within the lot.

3.4 Conduct a non-destructive test at each test site as soon as possible after placement without causing displacement. Calculate the thickness at each site, using the correction obtained in 2.4.1.d or 2.4.2.f.

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3.5 Average the results from the six (6) tests and note the number of individual test results below the design thickness.

3.6 Using portions 3, 4, and 5 of Alternative Specification I, determine the acceptance, penalties, or rejection of the lot.

3.7 Average the first five (5) test results and note the number of individual test results below the design thickness.

3.8 Determine the acceptance or rejection of the lot, using portions 3 and 4 of Alternative Specification II. If the results of 3.7 do not apply to portion 3 or 4 of this specification, conduct four (4) more tests in a random manner within the lot.

3.9 Average the ten (10) test results and note the number of individual test results below the design thickness.

3.10 Determine the acceptance, penalties, or rejection of the lot, using portions 6, 7, and 8 of Alternative Specification II.

Test Method for Determining the Depth of Reinforcement

1. Scope

1.1 This method covers the procedures for determining the depth of reinforcement below the surface of portland cement concrete, utilizing non-destructive test methods.

2. Apparatus

2.1 Non-destructive apparatus employed for determining the depth of reinforcement must have been proven capable of determining the depth with a standard deviation of less than one half (1/2) in.

2.2 The apparatus must be capable of determining depth of reinforcement from zero (0) to five (5) in.

2.3 The apparatus must be proven stable and the results repeatable to one eighth (1/8) in. over a temperature range of 40° to 120° F.

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3. Procedure

3.1 Turn the instrument on for the warm-up period recommended by the manufacturer.

3.2 In each one hundred (100) ft of pavement, take two (2) depth-to-reinforcement measurements between the striking-off and the finishing operations in a random manner.

4. Acceptance

4.1 If the depth to reinforcement is deficient by more than one half (1/2) in., notify the paving inspector in order that corrective action may be taken.

EVALUATION OF ACCEPTANCE SPECIFICATIONS
BY COMPUTER SIMULATION

Alternative Acceptance Specification Plans I and II, and a variation of Plan I having a sample size of 10 (designated IA), were subjected to computer simulation to produce operating characteristic (OC) curves from which the relative risks and efficiencies of the plans could be observed. Points on the OC curves were established for normally distributed populations having the following percentages of population values below the design criterion: 5, 12.5, 25, 37.5, 50, 62.5, 75, 87.5, and 95. All of the populations had a standard deviation of 0.34 in. This is the weighted mean standard deviation from published data (132,134) and from the Phase II field tests in this project. It represents pavement thickness measurements on 4,194 cores covering 46 projects in four states. For the same data, the thickness measurements averaged 0.21 in. greater than the specified thickness. For each of the nine abscissa values given above, 500 random samplings of the simulated population were accomplished by

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means of an electronic computer for each of the sampling plans. The resulting OC curves are presented on Figure E-3. Decile probability values based on Figure E-3 are given in Table E-5.

All acceptance sampling plans involve risks. The consumer's risk is the probability of accepting an inferior job, and the producer's risk involves the probability of having an acceptable job rejected. Therefore, to evaluate acceptance sampling plans, one must first define what constitutes an acceptable percentage of defectives in the job under consideration. For example, assume that one would accept, without penalty, jobs that are 10 percent defective, but not jobs that are 90 percent defective, even with penalty. Plan IA shows about a 24 percent producer's risk (without penalty) and about a 4 percent consumer's risk under these conditions. For Plans I and II the producer's risks are about 12 and 0 percent, and the consumer's risks are about 17 and 13 percent, respectively. Where defectives will not result in total failure or danger to life or property, it is common practice to accept producer's and consumer's risks of 5 and 10 percent, respectively. Therefore, using the criteria and conditions cited above, Plan I appears to be the best of the three. Plan IA is too harsh on the producer which would tend to increase construction costs. Sampling costs are also higher for Plan IA. Plan II has an insignificant risk to the producer. In other words, with 10 percent or less of the pavement deficient in thickness, there is virtually no risk to the producer that he will be penalized under Plan II. However, if 90 percent or more of the area is deficient in thickness, the consumer will accept it, with penalties, about 13 percent of the time and thus the consumer bears a significant risk of obtaining a totally unacceptable job while the producer enjoys no risk of being penalized on an acceptable job in Plan II.

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With regard to cost of sampling, it is immediately evident that Plan I requires less sampling than Plan IA (6 vs. 10 specimens per sample). Comparison with Plan II, however, is more difficult because Plan II is a double-sampling plan. In the computer simulated runs on the three sampling plans, a tabulation was kept on the number of cases in which the second step of Plan II had to be invoked. This information is illustrated on Figure E-4. Also, it will be recalled that data from the field and the literature indicated that, on the average, pavements are 0.21 in. thicker than specified with a standard deviation of 0.34 in. Assuming a normal distribution, one can readily determine that 27 percent of the population, on the average, falls below the design thickness. Referring to Figure E-4, it can be seen that, on the average, double sampling will have to be used 44 percent of the time. Therefore, the average sample size for Plan II is 5 + (0.44 x 5), or about 7. In terms of cost of sampling, then, the three plans in order of increasing cost are: I, II, and IA.

The use of the three sampling plans in conjunction with the Phase III field testing is described in Appendix F.

E-18

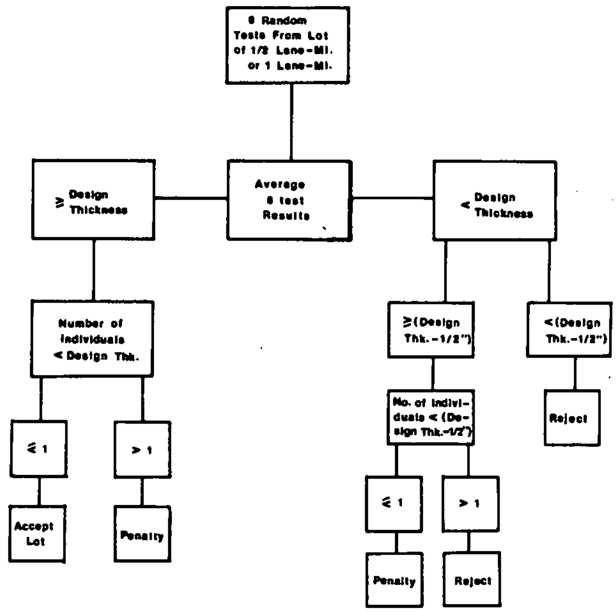

Figure E-1. Alternative Plan I.

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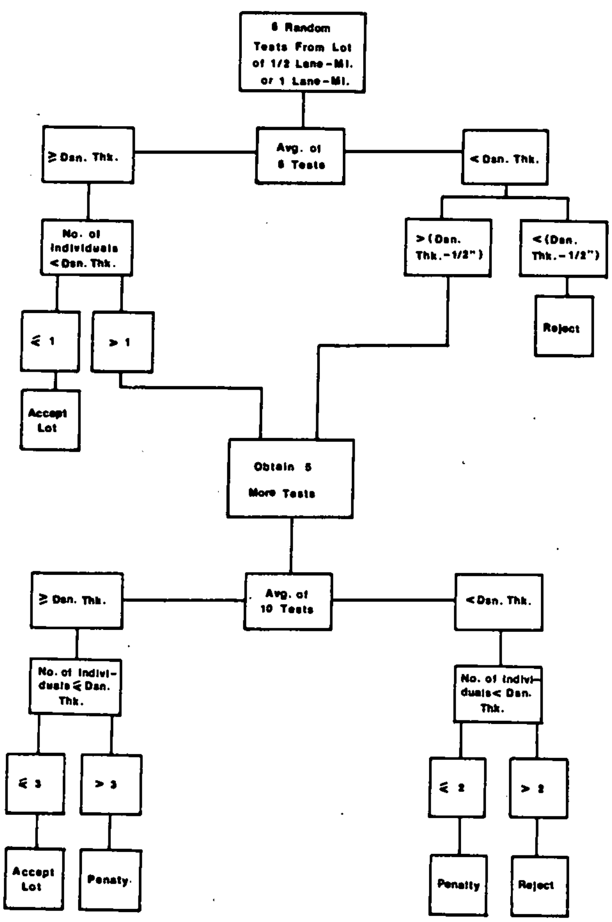

Figure E-2. Alternative Plan II.

E-20

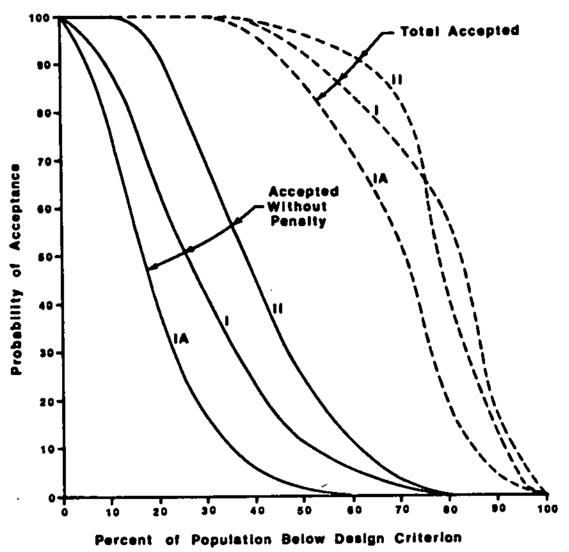

Figure E-3. Operating characteristic curves for Alternative Specifications I, IA, and II.

E-21

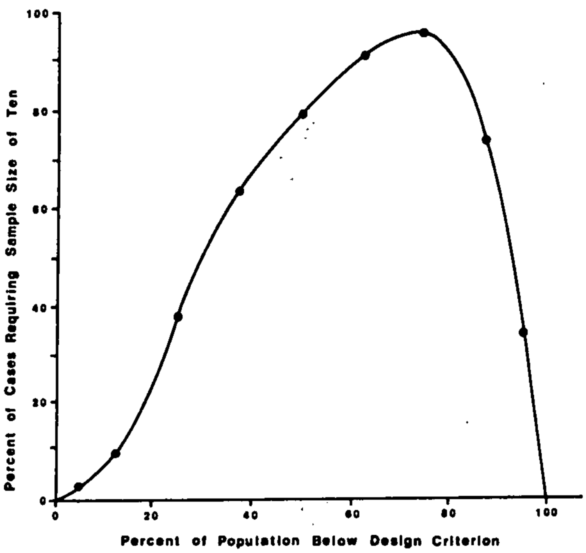

Figure E-4. Percentage of cases requiring sample size of ten (double sampling) in sampling Plan II.

E-22

Table E-1. State Requirements for Pavement Thickness Acceptance

State	Lot Size	Min. Cores/Lot	Tolerance, 100% Payment, in.
Alabama	1000 ft of 1 lane	1	-0.25
Alaska	1000 ft of 1 lane	1	-0.20
Arizona	1000 ft of 1 lane	1	-0.20
Arkansas	2000 sq yd of 1 lane	1	-0.50
California	1000 ft of 1 lane	1	-0.12
Colorado	1000 ft of 1 lane	1	-0.20
Connecticut	1000 ft of 1 lane	1	-0.25
Delaware	1000 ft of 1 lane	1	-0.20
Florida	800 ft of 1 lane	1	-0.50
Georgia	1000 ft of 1 lane	1	(a)
Hawaii	1000 ft of 1 lane	1	-0.20
Illinois	1000 ft of 1 lane	1	-0.20
Indiana	1000 ft of 1 lane	1	-0.50
Iowa	2500 sq yd of 1 lane	1	-0.25
Kansas	1000 ft of 1 lane	1	-0.20
Kentucky	1000 ft of 1 lane	1	-0.20
Louisiana	1000 ft of 1 lane	1	-0.20
Maine	1000 ft of 1 lane	1	-0.20
Maryland	1000 ft of 1 lane	(b)	(b)
Massachusetts	1000 ft of 1 lane	1	-0.25
Michigan	1000 ft of 2 lane	1	-0.20
Minnesota	1000 ft of 1 lane	1	-0.10
Mississippi	1000 ft of 1 lane	1	-0.20
Missouri	1 mile	10	-0.20 (avg)
Montana	1/2 mile of 2 lane	1	-0.125
Nevada	1000 ft of 1 lane	1	-0.12
New Hampshire	None	None	None
New Jersey	As directed by engineer	(c)	None
New York	1000 ft of 1 lane	1	-0.50
North Carolina	1000 ft of 1 lane	1	-0.20
North Dakota	4000 sq yd of 1 lane	1	-0.20
Ohio	2000 sq yd of 1 lane	1	-0.10
Oklahoma	1000 ft of 1 lane	1	-0.20
Oregon	1000 ft of 1 lane	1	-0.20
Pennsylvania	3000 sq yd of 1 lane	1	-0.25
South Carolina	1000 ft of 1 lane	1	-0.20
South Dakota	1000 ft of 1 lane	1	-0.20
Tennessee	1000 ft of 1 lane	1	-0.25
Texas	None	(c)	-0.25
Virginia	None	(c)	-0.20
Washington	1 mile of 1 lane	2	-0.25
West Virginia	None	None	None
Wisconsin	1000 ft of 1 lane	1	-0.20
Wyoming	1000 ft of 1 lane	1	-0.20

[a] Percent payment = percent thickness (all areas)
[b] Not stated
[c] As directed by engineer

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Table E-2. Penalties Based on the Number of Test Results Below Design Thickness

Using 6 Tests: No. Tests Deficient	Using 6 Tests: Percent Payment	Using 10 Tests: No. Tests Deficient	Using 10 Tests: Percent Payment
0-1	100	0-3	100
2-3	88	4-6	88
4-5	75	7-8	75
6	50	9-10	50

Table E-3. Penalties Based on the Percentage of Design Thickness Actually Placed

Use equation: $(t/T)C$ = payment (not to exceed contract price)

where
t = average measured thickness, in.
T = design thickness, in.
C = contract price

Table E-4. Penalties Based on the Reduction in Pavement Life

11 in. Design Thickness: Average Test Thickness, in.	Percent Payment	10 in. Design Thickness: Average Test Thickness, in.	Percent Payment
11.0	100.0	10.0	100.0
10.9	95.5	9.9	95.1
10.8	91.2	9.8	90.4
10.7	87.0	9.7	85.9
10.6	83.0	9.6	81.5
10.5	79.2	9.5	77.4

9 in. Design Thickness: Average Test Thickness, in.	Percent Payment	8 in. Design Thickness: Average Test Thickness, in.	Percent Payment
9.0	100.0	8.0	100.0
8.9	94.5	7.9	93.9
8.8	89.3	7.8	88.1
8.7	84.4	7.7	82.6
8.6	79.6	7.6	77.3
8.5	75.1	7.5	72.4

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Table E-5. Acceptance and Rejection Probability Values Based on OC Curves

% of Pop. Below Dsn.	Acceptance Without Penalty I	Acceptance Without Penalty IA	Acceptance Without Penalty II	Acceptance With Penalty I	Acceptance With Penalty IA	Acceptance With Penalty II	Acceptance Total I	Acceptance Total IA	Acceptance Total II	Rejection I	Rejection IA	Rejection II
10	88	76	100	12	24	0	100	100	100	0	0	0
20	65	38	96	34	61	4	99	99	100	1	1	0
30	42	16	69	57	83	30	99	99	99	1	1	1
40	23	5	45	75	90	54	98	95	99	2	5	1
50	12	1	24	81	84	72	93	85	96	7	15	4
60	6	0	11	78	71	81	84	71	92	16	29	8
70	2	0	3	71	51	79	73	51	82	27	49	18
80	0	0	0	58	18	41	58	18	41	42	82	59
90	0	0	0	17	4	13	17	4	13	83	96	87

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APPENDIX F

PHASE III FIELD STUDIES

INTRODUCTION

Upon completion of the Phase II field studies, the most promising candidate measures were selected for comprehensive field evaluation. On the basis of the findings of the Phase II studies, the Ohio State ultrasonic gage and the eddy current proximity gage were recommenoed for use in determining pavement thickness, and the pachometer was recommended for use in determining reinformcement location.

PROCEDURE

Several state highway agencies were contacted regarding the possibility of performing a test program on a project within their respective states. Consideration was given to the following factors in each cooperating state: use of reinforcement, type of concrete and aggregate used, and type of subbase. A total of eight construction projects was finally selected for use as test sites (Table F-1).

The four acceptance sampling specifications (three for pavement thickness; one for reinforcement location), discussed in Appendix E, were evaluated during paving operations on the eight jobs to determine their performance in giving one-day acceptance or rejection of pavement thickness and reinforcement location. The results obtained using the new specifications were compared with the present acceptance procedure in each state. The performance of each gage on each job was also noted.

F-2

OPERATION OF THE GAGES

Eddy Current Proximity Gage

The eddy current proximity gage operated very well on nonreinforced concrete paving. The use of 3-ft-sq aluminum window screen in place of the sheet aluminum previously employed has worked very well. In placing the screen on the subbase several nails were used at the edges. Then, an inch or more of plastic concrete was placed by shovel on top of the screen just prior to the paving. As soon as the paving had set sufficiently to be walked on, a reading was obtained. The gage operated well, without equipment failures in the field. If the screen is placed near the edge of the pavement or if travelling foot bridges are available, tests may be made immediately behind the paving train. It should be noted, however, that obtaining readings only along the edge of the pavement violates the principle of random sampling. In this study, the concept of immediate testing behind the paving operations was abandoned in favor of acceptance or rejection within 24 hours. Attempts to test the plastic concrete generally interfered with the contractor's paving operations, resulting in confusion and needless delays.

Ohio State Ultrasonic Gage

The Ohio State ultrasonic gage employed in this study consisted of sensitive laboratory-type components and, thus, was subject to numerous equipment breakdowns under the harsher conditions encountered in the field. If produced commercially, it is expected that this problem would be greatly reduced. The seating of the transducers of this gage on a rough concrete surface has caused some problems in obtaining transmission

F-3

of the ultrasonic pulses through the contact zone. This was overcome, where necessary, by grinding the test sites. However, this results in an objectionable smooth spot on the pavement surface. Other methods of assuming a coupling between the ultrasonic gage and the concrete were also utilized with varying success.

The overall results with the Ohio State gage were quite satisfactory. However, it was found to give poor results, in terms of erratic and poorly defined signals for concrete pavements over bituminous concrete subbase (I-10 in Louisiana, the Maryland overlay and the 6-in.-thick portion of the Pennsylvania jobs). This necessitated the use of a calibration factor for the I-10 data--the only case in which a calibration factor was required in the Phase III studies. The reason for this problem is not clear at this time. Actually, problems of this nature would, more logically, be expected where cement stabilized subbase is used. However, no such problems were encountered at either Louisiana Essen Lane nor Utah I-15 where cement stabilized subbase was used. It is thought that perhaps the asphalt seal coat used on the cement-treated subbase provided sufficient demarcation between the pavement and subbase to give clear indications of pavement thickness, while the bituminous concrete subbase diffused the sound energy to the extent that it was very difficult to obtain a clear reflection signal.

Pachometer

The pachometer operated very well in locating the position of reinforcement wherever used.

F-4

PAVEMENT THICKNESS MEASUREMENTS

General

Pavement thickness measurements, as determined from coring, using the Ohio State ultrasonic gage and the eddy current proximity gage are presented on Tables F-2, F-3, and F-4, respectively. The same sample numbers for each location for the three different methods of measurement correspond to the same test section of highway pavement. Notice that specimen numbers do not necessarily correspond to the same exact location within the test areas for the different methods of measurement. It was not practical, nor was it intended, to compare the readings on a one-to-one basis. Rather, the individual readings are arranged within their respective rows (test areas) in order of random selection, by an electronic computer, to facilitate the application of the proposed methods of acceptance testing.

Application of Acceptance Test Methods

The current acceptance criteria for pavement thickness for each of the six states involved in this study are summarized on Table F-5. The details of three alternative sets of acceptance criteria proposed for study here were presented in Appendix E. Briefly, Alternate I consists of taking 6 readings representing 1/2 lane-mi. and averaging them. If the average value is equal to, or greater than, the specified thickness and no more than 1 reading is less than the specified thickness, the pavement section is accepted. If more than 1 reading is less than the specified thickness, a penalty is assessed. If the average of the 6 readings is less than the specified value and no more than 1 reading is less than the specified thickness minus 1/2 in., the pavement section is accepted with a penalty being assessed. However, if more than 1 reading, or if the average of the 6 readings, is less than the specified thickness minus 1/2 in., the pavement section is rejected. Alternate Method IA is the same as Alternate Method I, except that the sample size is increased from 6 to 10. Acceptance and rejections limits remain the same. Thus, it is a considerably more stringent specification than Alternate I.

Alternate Specification II is a double-sampling plan in which 5 readings are first examined for the given pavement section. Depending on the resulting average thickness and the number of individual readings that fall below the specified thickness, the pavement will either be accepted or rejected, or 5 more readings will be averaged in to give a total of 10. In the latter instance, acceptance, rejection, or the application of a penalty is again determined by the average thickness and the number of readings failing to equal or exceed the design thickness or the design thickness minus 1/2 in. The flow diagrams presented as Figures E-1 and E-2 in Appendix E clearly illustrate the details of the proposed alternative sampling plans.

Table F-6 summarizes the results of the application of the three proposed alternative acceptance specifications and the existing state specification in each state to the data shown in Tables F-2, F-3, and F-4. It is interesting to notice that, while the existing state specifications applied to core data would have accepted all test sections, proposed Alternate Specifications I, IA, and II would have resulted in penalties being applied in 8 percent, 23 percent, and 4 percent of the

cases, respectively. This result points up two things: first, existing state specifications are probably not effective in assuring quality control with regard to pavement thickness; and second, as pointed out in Appendix E, Alternate Specification IA is much too severe on the producer.

Table F-7 summarizes the actions indicated by the State Specifications and the proposed alternative methods for the pavement thickness data obtained in this study by Ohio State ultrasonic gage and eddy current proximity gage as well as by coring. Ignoring for the moment the eddy current proximity data, due to the small quantity of data there, a comparison of the actions indicated by the various specifications between coring and Ohio State gage measurement shows rather disheartening lack of agreement, especially in the Alternate I method. However, since the mean standard deviations of the cores and Ohio State gage readings are found to be small (0.268 in. and 0.275 in., respectively) and not significantly different by Student's t-test, appropriate standardization of the Ohio State gage should eliminate this problem. Also, it is quite possible that the Ohio State gage readings are actually more accurate than the cores because of the propensity of the cores to retain some subbase material at the bottom faces.

The fresh concrete on the Louisiana I-10 job was also probed for pavement thickness. These data, along with a summary of actions indicated by the three proposed specifications is shown on Table F-8. It will be noticed that actual probing of pavement depth during placing does not correlate very well with core measurements either. Notice that the Ohio State gage measurements on this job were adjusted with a

correction factor relating core lengths to ultrasonic readings, and thus good correspondence between those two would be expected here. This serves to strengthen the argument that core readings may not be as reliable as commonly assumed.

The eddy current proximity data are also consistent, indicating here too that proper calibration of the equipment should facilitate its use as a practical, non-destructive test tool.

Application of Penalties

The three alternative methods of applying penalties to pavement thicknesses failing to conform to specifications, as presented in Tables E-2, E-3, and E-4 of Appendix E, were applied to the Ohio State gage and core thickness determinations from the Phase III field studies. The results are presented on Table F-9. While the data presented are too meager to provide firm conclusions, it appears that the method based on the number of test results below design thickness using six tests is too severe on the contractor. On the other hand, the method based on percentage of design thickness appears to be too lenient. It is felt that the method and use of penalties should be the prerogative of the individual states. Three rational methods for accomplishing this are illustrated here.

REINFORCEMENT LOCATION MEASUREMENTS

General

Reinforcement location measurements using the pachometer were obtained on the Minnesota I-35 job, the Ohio I-580 job, and the Pennsylvania SR-157 job. The only other of the eight jobs that had

reinforcement, Maryland I-70N, was not tested for reinforcement location. The test data are presented on Table F-10.

Application of Acceptance Test Methods

The current acceptance criteria for depth of reinforcement in pavement slabs are presented on Table F-11. The acceptance sampling method and criteria proposed in this research is that the average of two readings taken at random for each 100 lane-ft of pavement must equal or exceed the specified value minus 1/2 in. (see Appendix E). The applications of these criteria to the data are also shown on Table F-10. Because of the excessive depth of the reinforcement in the Ohio job, those data are meaningless. The usefulness of the pachometer is limited to about 5 in. in depth. However, in the Minnesota and Pennsylvania jobs the data show good control in maintaining concrete cover over the reinforcement.

Since reinforcement depths were not verified by coring, there is no way to check the accuracy of the pachometer readings. However, this point was well established in the earlier work conducted in Phases I and II of this project.

One interesting sidepoint can be observed in the Pennsylvania data where the specified minimum depth was 2-1/2 in. The bars and strands in continuously reinforced sections of this pavement showed average depths of 3.42 in. and 3.16 in. with standard deviations of 0.135 in. and 0.182 in., respectively. The welded wire fabric reinforced sections of this pavement, however, while showing about the same average depth (3.37 in.), had a considerably larger standard deviation (0.577 in.).

This would be expected and was previously observed in this research, but it serves here to indicate that the pachometer was functioning properly and with sufficient sensitivity.

It would appear from these somewhat limited data that reinforcement position in concrete pavement presents no serious problem either in terms of the frequency of occurrence of inadequate cover or in terms of non-destructive determinations using the pachometer.

Table F-1. Construction Projects in Phase III Study

State	Route	Design Thickness (in.)	Reinforcement	Subbase Type
Louisiana	I-10 (Lafayette)	10	None	Hot-mixed bituminous concrete
	Essen Lane	8	None	Cement stabilized
Maryland	I-70N	6*	CRCP	Old PCC with hot-mixed bituminous leveling mix
Minnesota	I-35	9	Welded wire fabric	Gravel
	SR-56	7	None	Gravel
Ohio	I-580	10	Bars	Slag
Pennsylvania	SR-157	9	Welded wire fabric	Crushed stone
			CRCP	Hot-mixed bituminous concrete
Utah	I-15	10	None	Cement stabilized

*Overlay

Table F-2. Phase III--Core Data

Location	Sample No.	Specimens (Random Order) 1	2	3	4	5	6	7	8	9	10	11	12	Average first 6	first 5	first 10	Specified thick.
Louisiana, I-10	1	10.65	10.70	10.25	10.30	10.60	10.15	10.10	10.50	10.30	10.40			10.44	10.50	10.40	10
	2	10.45	10.20	10.35	10.50	10.20	10.15	10.20	10.45	10.45	10.15			10.31	10.34	10.31	10
	3	10.55	10.25	10.05	10.65	10.30	10.35	10.85	10.55	10.30	10.15	10.00	10.50				
												10.75	10.15	10.36	10.36	10.40	10
	4	10.40	10.55	10.25	10.35	10.45	10.10	10.25	10.85	9.90	10.65			10.35	10.40	10.38	10
	5	10.10	10.00	10.15	10.35	10.50	10.65	10.10	10.30	10.40	10.50			10.29	10.22	10.31	10
	6	10.25	10.10	10.05	10.45	10.30	10.35	10.15	10.20	10.35	10.55	10.35	10.35				
											10.45	10.35	10.35	10.25	10.23	10.28	10
La., Essen Lane		NO CORE DATA AVAILABLE															8
Maryland, I-70N	1	6.5	6.3	6.1	6.0	6.1	5.9							6.15	6.16	*	6
	2	6.0	6.7	6.2	6.8	6.4	6.0							6.35	6.38	*	6
Minnesota, I-35	1	9.38	9.19	8.85	9.26	9.24	9.36	9.41	9.24	9.01	8.91			9.21	9.18	9.19	9
	2	9.39	9.22	9.55	9.86	9.65	8.49	8.90	9.16	8.90	9.50			9.36	9.53	9.26	9
	3	9.23	9.28	9.04	9.29	9.40	9.72	9.08	9.64	9.34	9.36			9.33	9.25	9.34	9
	4	9.26	9.16	9.47	9.17	9.28	9.14	9.60	9.00	9.45	9.34	9.46	9.49	9.25	9.27	9.29	9
Minnesota, SR-56	1	7.05	7.78	6.84	6.89	7.97	7.33	7.63	7.70	7.00	7.20			7.31	7.31	7.34	7
	2	7.29	6.78	7.13	7.29	7.33	7.28	7.15	7.37	7.31	7.01			7.18	7.16	7.19	7
	3	7.36	7.30	7.17	7.29	7.51	7.74	7.09	7.07	6.89	7.79			7.38	7.31	7.31	7
Ohio, I-580	1	11.40	10.20	10.80	10.50	11.00	10.60	10.90	10.30	10.10	10.80	10.40	10.00	10.75	10.78	10.66	10
Penna., SR-157	1	10.00	9.10	9.20	9.70	9.00	9.70	9.20	9.80	9.75	9.90			9.45	9.40	9.54	9
	2	10.40	9.40	9.70	9.55	9.50	8.75	9.50	9.20	9.80	9.70			9.55	9.71	9.55	9
	3	9.50	9.70	10.00	9.60	9.50	9.80	9.50	9.65	9.80	9.60			9.68	9.66	9.67	9
	4	5.35	9.40	9.60	9.20	10.00	9.70	9.60	9.50	9.10	9.60			9.54	9.51	9.51	9
Utah, I-15	1	9.50	10.25	10.00	10.07	10.00	9.75	10.25	10.50	9.50	9.50	10.00	10.00	9.93	9.97	9.93	10
	2	10.00	10.38	10.00	10.00	10.25	9.75	10.00	9.75	10.50	10.25			10.06	10.13	10.09	10
	3	10.50	10.12	10.25	10.50	10.00	10.25	10.50	10.50	9.75	10.50	10.00		10.27	10.27	10.29	10
	4	9.75	10.00	10.00	10.50	10.00	10.50	10.50	10.50	10.00	10.00			10.13	10.05	10.18	10

*Insufficient data

Table F-3. Phase III--Ohio State Ultrasonic Gage Data

Location	Sample No.	Specimens (Random Order) 1	2	3	4	5	6	7	8	9	10	11	12	Average first 6	first 5	first 10	Specified thick.
Louisiana, I-10*	2	10.20	10.22	10.12	10.22	10.41	10.14	10.14	10.27	10.34	10.12			10.22	10.23	10.22	10
	3	10.10	9.88	10.38	10.26	10.39	11.01	10.08	10.42	10.04	12.40			10.34	10.20	10.50	10
La., Essen Lane	1	8.68	8.62	8.48	8.66	8.57	8.59	8.53	8.53	8.57	8.42			8.60	8.60	8.57	8
	2	8.12	8.52	8.59	8.40	8.36	9.45	8.22	8.60	8.57	8.84			8.57	8.40	8.57	8
Maryland, I-70N	1	6.23	6.23	6.26	6.26	6.18	6.36	6.31	6.27	6.16	5.63			6.25	6.23	6.19	6
	2	6.21	6.23	6.21	6.21	6.33	6.25	6.11	6.18	6.32	6.21			6.24	6.24	6.23	6
Minnesota, I-35	1	9.02	8.52	8.96	9.14	9.28	9.07	8.96	9.25	9.19	9.10			9.00	8.98	9.05	9
	2	9.21	9.09	9.05	9.35	9.60	9.99	9.18	9.25	9.23	9.15			9.38	9.26	9.31	9
	3	9.30	9.34	9.34	8.96	8.94	9.11	9.23	9.16	9.12	9.13	9.39	8.91				
											8.79	9.09	9.38	9.17	9.18	9.16	9
Minnesota, SR-56	1	7.20	7.18	7.88	7.41	7.04	7.20	7.06	7.21	7.21	7.56			7.32	7.34	7.30	7
	2	7.03	7.24	7.26	7.15	8.01	7.00	6.99	7.00	7.00	7.58			7.28	7.34	7.23	7
	3	7.27	7.27	7.13	7.34	7.30	7.13	7.14	7.47	7.24	7.29			7.24	7.26	7.26	7
Ohio, I-580	1	9.74	9.81	10.60	9.93	10.50	9.88	9.89	9.57	10.22	11.36	9.28	10.40				
												10.50	10.04	10.07	10.12	10.15	10
Penna., SR-157	1	9.23	9.04	9.17	9.23	9.07	9.15	9.35	9.07	9.04	9.11			9.15	9.15	9.15	9
	2	9.22	9.13	9.23	9.33	9.10	9.29	8.98	9.06	9.04	8.75			9.22	9.20	9.11	9
	3	9.36	9.18	9.26	9.31	9.40	9.13	9.15	9.10	9.19				9.27	9.30	**	9
	4	9.20	9.14	9.23	9.45	9.63	9.31	9.23	9.28	9.42				9.33	9.35	**	9
Utah, I-15	1	9.40	9.40	9.27	10.22	9.92	10.16	10.07	9.74	10.06	8.82			9.73	9.64	9.71	10
	2	10.02	10.08	10.16	10.49	10.00	10.08	10.01	9.86	9.77	9.89	9.68		10.14	10.15	10.04	10
	3	10.41	9.96	9.88	10.42	9.64	11.38	9.24	10.15	9.76	10.28			10.28	10.06	10.11	10
	4	9.88	10.40	9.92	9.84	9.74	9.84	11.20						9.94	9.96	**	10

* Conversion factor of x 1.069 used

**Insufficient data

Table F-4. Phase III--Eddy Current Proximity Gage Data

Location	Sample No.	Specimens (Random Order) 1	2	3	4	5	6	7	8	9	10	11	12	Average first 6	first 5	first 10	Specified thick.
Louisiana, I-10	2	10.26	10.58	10.10	10.10	9.84	10.26	10.10	10.58	10.82	10.58			10.19	10.18	10.32	10
	3	9.84	10.10	9.84	10.10	9.58	10.10	10.10	9.84	9.84				9.93	9.89	*	10
La., Essen Lane	1	8.56	8.30	8.56	8.30	8.56	8.04	8.30	9.02	8.56	8.80			8.39	8.46	8.50	8
Minnesota, SR-56	1	6.55	6.80	7.10	7.10	7.10	7.10	7.10	7.10	7.10	6.95			6.96	6.93	7.00	7
	2	6.95	7.25	7.10	7.10	7.25	7.10	7.10	7.10	7.10	7.25			7.13	7.13	7.13	7
	3	7.10	7.10	7.10	6.80	6.95	7.10	7.10	6.95	6.80	6.80			7.03	7.01	6.98	7
	4	7.10	7.10	6.80	6.95	6.95	6.95	6.95	7.10	7.10				6.98	6.98	*	7
Utah, I-15	1	10.9	10.9	10.6	11.3	10.6	10.9							10.87	10.86	*	10
	2	10.6	10.6	10.6	10.6	10.6	10.9	10.9	10.5	10.6	10.9	10.3	10.5				
													10.3	10.65	10.60	10.68	10
	3	10.3	10.6	10.9	10.5	11.3	10.6	10.5	10.3					10.70	10.72	*	10
	4	10.6	10.9	10.9	10.6	10.8	11.3	10.9						10.85	10.76	*	10

*Insufficient data

Table F-5. Current State Acceptance Criteria for Pavement Thickness

State	Maximum Area or Length	Minimum Sample Size	Specification Limits Min. Accept.	Penalty Range	Rejection
Louisiana	1,000 ft of one lane	1	-0.20 in.		
Maryland	1,000 ft of one lane	1	(...................... not specified ....)		
Minnesota	1,000 ft of one lane	1	-0.1 in.		
Ohio	2,000 sq. yd.	1[a]	-0.1 in.	-0.2 in. to -0.5 in.	<-0.5 in.
Pennsylvania	3,000 sq. yd.	1	-0.25 in.	-0.26 in. to -0.50 in.	<-0.5 in.
Utah	50,000 sq. ft.	4	-0.25 in.[b]	-0.26 in. to -1.00 in.[c]	<-1.00 in.[c]

[a] Minimum of 3 for entire pavement

[b] Average of 4 cores; No one core deficient by more than 0.5 in.

[c] Average of 4 cores

Table F-6. Summary of Pavement Thickness Measurements

Location	Specified Thickness	Cores Sample	Cores Avg. of 6	Cores Acceptance Spec. I	IA	II	Existing State Spec.	Ultrasonic Sample	Ultrasonic Avg. of 6	Ultrasonic Acceptance Spec. I	IA	II	Eddy Current Proximity Sample	Avg. of 6	Acceptance Spec. I	IA	II
Louisiana, I-10	10	1	10.44	A	A	A	A										
	10	2	10.31	A	A	A	A	2	10.22+	A	A	A	2	10.19	A	A	A
	10	3	10.36	A	A	A	A	3	10.34+	A	A	A	3	9.93	P	*	*
	10	4	10.35	A	A	A	A										
	10	5	10.29	A	A	A	A										
	10	6	10.25	A	A	A	A										
La., Essen Lane	8							1	8.60	A	A	A	1	8.39	A	A	A
	8							2	8.57	A	A	A					
Maryland, I-70N	6	1	6.15	A	*	A	A	1	6.25	A	A	A					
	6	2	6.35	A	*	A	A	2	6.24	A	A	A					
Minnesota, I-35	9	1	9.21	A	P	A	A	1	9.00	P	P	A					
	9	2	9.36	A	P	A	A	2	9.38	A	A	A					
	9	3	9.33	A	A	A	A	3	9.17	P	P	A					
	9	4	9.25	A	A	A	A										
Minnesota, SR-56	7	1	7.31	P	P	A	A	1	7.32	A	A	A	1	6.96	P	P	P
	7	2	7.18	A	A	A	A	2	7.28	A	A	A	2	7.13	A	A	A
	7	3	7.38	A	A	A	A	3	7.24	A	A	A	3	7.03	P	P	P
	7												4	6.98	P	*	*
Ohio, I-580	10	1	10.75	A	A	A	A	1	10.08	P	P	P					
Penna., SR-157	9	1	9.45	A	A	A	A	1	9.15	A	A	A					
	9	2	9.55	A	A	A	A	2	9.22	A	P	A					
	9	3	9.68	A	A	A	A	3	9.27	A	*	A					
	9	4	9.54	A	A	A	A	4	9.33	A	*	A					
	6							1	*	*	*	A					
Utah, I-15	10	1	9.93	P	P	P	A	1	9.73	R	R	R	1	10.87	A	*	A
	10	2	10.06	A	P	A	A	2	10.14	A	P	A	2	10.65	A	*	A
	10	3	10.27	A	A	A	A	3	10.28	P	P	P	3	10.70	A	*	A
	10	4	10.13	A	A	A	A	4	9.94	P	*	*	4	10.85	A	*	A

Key: A = Accepted
P = Accepted with penalty
R = Rejected

+ = x 1.069 conversion factor
* = Insufficient data

Table F-7. Summary of Actions Indicated by Specifications

Specification	Action	% of Cases Action Indicated Cores	Ultrasonic	ECPC
I	Accept	92	71	64
	Penalty	8	24	36
	Reject	0	5	0
IA	Accept	77	61	60
	Penalty	23	33	40
	Reject	0	6	0
II	Accept	96	86	78
	Penalty	4	9	22
	Reject	0	5	0
State	Accept	100		
	Penalty	0		
	Reject	0		

Table F-10. Summary of Reinforcement Location Data by Pachometer

Location	Representing Station No.	No. of Rdgs.	Avg.	Std. Dev.	Representative Rdgs.* 1	2	Acceptance Spec.** State	Proposed
Minnesota, I-35	1086	2			4.2	4.2	A/A	A
	1087	2			5.2	3.6	A/A	A
	1088	2			5.2	4.2	A/A	A
	1089	2			4.2	4.2	A/A	A
	1090	2			4.2	5.2	A/A	A
	1091	2			4.2	4.2	A/A	A
	1092	2			5.2	4.2	A/A	A
	1093	2			4.2	3.6	A/A	A
	1094	2			3.6	5.2	A/A	A
	1095	2			4.2	4.2	A/A	A
	1096	2			3.6	4.2	A/A	A
	1097	2			4.2	3.6	A/A	A
	1098	2			5.2	5.2	A/A	A
	1099	2			5.2	4.2	A/A	A
	1100	2			5.2	5.2	A/A	A
	1101	2			4.2	4.2	A/A	A
	1102	2			4.2	4.2	A/A	A
	1103	2			4.2	3.6	A/A	A
	1104	2			4.2	5.2	A/A	A
	1105	2			3.6	5.2	A/A	A
	1106	2			4.2	5.2	A/A	A
	1107	2			3.6	4.2	A/A	A
	1108	2			3.6	4.2	A/A	A
	1109	2			5.2	4.2	A/A	A
	1110	2			4.2	5.2	A/A	A
	1111	2			4.2	4.2	A/A	A
	1112	2			3.6	4.2	A/A	A
	1113	2			3.6	3.6	A/A	A
	1114	2			4.2	3.6	A/A	A
	1115	2			4.2	4.2	A/A	A
	Overall	60	4.32	0.565				

Table F-10. Continued

Location	Representing Station No.	No. of Rdgs.	Avg.	Std. Dev.	Representative Rdgs.* 1	2	Acceptance Spec.** State	Proposed
Ohio, I-580	1244 WB	1			>6.5		A	
	1243 WB	2			2.7	6.5	R/A	A
	1242 WB	2			>6.5	2.3	A/R	A
	1241 WB	2			>6.5	>6.5	A/A	A
	1240 WB	2			>6.5	>6.5	A/A	A
	1239 WB	2			>6.5	>6.5	A/A	A
	1238 WB	2			>6.5	2.8	A/R	A
	1237 WB	2			>6.5	3.6	A/R	A
	1236 WB	2			>6.5	>6.5	A/A	A
	1235 WB	2			>6.5	>6.5	A/A	A
	1234 WB	2			>6.5	>6.5	A/A	A
	1233 WB	2			>2.9	>6.5	R/A	A
	1232 WB	2			>6.5	>6.5	A/A	A
	1231 WB	2			>6.5	>6.5	A/A	A
	1230 WB	2			>6.5	2.3	A/R	A
	1290 WB	2			>6.5	>6.5	A/A	A
	1291 WB	2			>6.5	5.4	A/A	A
	1292 WB	2			>6.5	>6.5	A/A	A
	1237 EB	2			>6.5	>6.5	A/A	A
	1238 EB	2			>6.5	3.1	A/R	A
	1239 EB	2			>6.5	>6.5	A/A	A
	1240 EB	2			>6.5	>6.5	A/A	A
	1241 EB	2			2.0	>6.5	R/A	R
	1242 EB	2			3.5	>6.5	R/A	A
	1243 EB	2			>6.5	>6.5	A/A	A
	1293 EB	2			3.6	3.0	R/R	R
	1294 EB	2			>6.5	2.5	A/R	A
Penna. SR-157	890 (strand)	20	3.30	0.248	3.00	3.31	A/A	A
	890 (bar)	20	3.49	0.268	3.44	3.38	A/A	A
	891 (strand)	20	3.20	0.107	3.31	3.00	A/A	A
	891 (bar)	20	3.40	0.048	3.44	3.38	A/A	A
	892 (strand)	20	3.06	0.153	3.00	3.19	A/A	A

Table F-8. Summary of Probe Data of Fresh Concrete, Louisiana I-10 Job

Sample No.	Corresponding Core Sample No.	Number of Specimens	Average Thickness	Acceptance Spec. I	IA	II
1	1	10	10.19	P	P	A
2	1	10	10.14	A	P	A
3	2	10	10.12	P	P	A
4	2	10	10.29	A	P	A
5	3	10	10.20	A	A	A
6	3	14	10.19	A	A	A
7	4	10	10.28	A	A	A
8	4	10	10.25	P	P	A
9	4	12	10.23	A	A	A
10	5	10	10.16	A	A	A
11	5	10	10.26	A	A	A
12	6	16	10.37	A	P	A
13	6	10	10.18	P	P	A

Key: A = Accepted
P = Accepted with penalty
R = Rejected

Table F-9. Application of Penalties

Location	Test Method	Sample No.	Based on No. of Test Results below Dsn. Using 6 Tests	Using 10 Tests	Based on % of Dsn. Using Avg. of 6 Tests	Based on Reduction in Pavement Life Using 6 Tests
Minn. I-35	OSG	2	88.	100.	100.0	100.0
Ohio I-580	OSG	1	75.	88.	100.0	100.0
Utah I-15	OSG	1	75.	88.	97.3	87.3
Utah I-15	OSG	3	88.	88.	100.0	100.0
Utah I-15	OSG	4	75.	*	99.4	97.1
Utah I-15	Cores	1	88.	88.	99.3	96.6

*Insufficient data

Table F-10. Continued

Location	Representing Station No.	No. of Rdgs.	Avg.	Std. Dev.	Representative Rdgs.* 1	Representative Rdgs.* 2	Acceptance Spec.** State	Acceptance Spec.** Proposed
Penna. (Cont.)	892 (bar)	20	3.38	0.070	3.38	3.44	A/A	A
	893 (strand)	20	3.16	0.137	3.13	3.19	A/A	A
	893 (bar)	20	3.42	0.057	3.38	3.38	A/A	A
	894 (strand)	20	3.07	0.119	3.19	3.00	A/A	A
	894 (bar)	20	3.39	0.059	3.44	3.31	A/A	A
	Strand overall	100	3.16	0.182				
	Bar overall	100	3.42	0.135				
	896 WB (mesh)				3.6	3.6	A/A	A
	897 WB (mesh)				3.8	3.8	A/A	A
	898 WB (mesh)				3.1	3.8	A/A	A
	906 WB (mesh)				3.4	3.6	A/A	A
	907 WB (mesh)				3.0	3.8	A/A	A
	908 WB (mesh)				3.3	3.8	A/A	A
	909 WB (mesh)				3.0	3.6	A/A	A
	910 WB (mesh)				2.7	3.4	A/A	A
	911 WB (mesh)				3.0	3.3	A/A	A
	912 WB (mesh)				3.0	3.0	A/A	A
	913 WB (mesh)				3.3	3.3	A/A	A
	914 WB (mesh)				3.8	4.2	A/A	A
	915 WB (mesh)				2.9	3.6	A/A	A
	916 WB (mesh)				3.8	3.3	A/A	A
	917 WB (mesh)				2.7	3.8	A/A	A
	918 WB (mesh)				2.8	4.2	A/A	A
	919 WB (mesh)				2.75	3.6	A/A	A
	920 WB (mesh)				2.6	3.6	A/A	A
	921 WB (mesh)				3.1	3.6	A/A	A
	922 WB (mesh)				2.75	3.3	A/A	A
	928 WB (mesh)				2.8	3.3	A/A	A
	929 WB (mesh)				3.0	3.0	A/A	A
	932 WB (mesh)				3.1	2.6	A/A	A

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Table F-10. Continued

Location	Representing Station No.	No. of Rdgs.	Avg.	Std. Dev.	Representative Rdgs.* 1	Representative Rdgs.* 2	Acceptance Spec.** State	Acceptance Spec.** Proposed
Penna. (Cont.)	935 WB (mesh)				2.8	3.1	A/A	A
	937 WB (mesh)				2.8	3.3	A/A	A
	938 WB (mesh)				3.6	2.7	A/A	A
	941 WB (mesh)				3.6	3.8	A/A	A
	942 WB (mesh)				3.8	4.2	A/A	A
	918 EB (mesh)				2.15	3.3	R/A	A
	917 EB (mesh)				2.7	2.2	A/R	A
	916 EB (mesh)				3.3	2.7	A/A	A
	915 EB (mesh)				3.1	3.8	A/A	A
	914 EB (mesh)				5.5	5.5	A/A	A
	913 EB (mesh)				4.2	3.8	A/A	A
	912 EB (mesh)				3.3	3.3	A/A	A
	911 EB (mesh)				3.6	3.6	A/A	A
	907 EB (mesh)				3.8	3.05	A/A	A
	906 EB (mesh)				3.0	3.6	A/A	A
	Mesh overall	76	3.37	0.577				

*Randomly Selected

**A = Accepted; R = Rejected

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Table F-11. Current State Acceptance Criteria for Reinforcement Location

State	Acceptance Criteria*
Minnesota	1-1/2 in. to 5-1/2 in.
Ohio	5 in. (minimum cover)
Penna.	One-fourth of pavement thickness + 1/4 in. (minimum cover)

*See Table E-1 for sampling frequency.

F-23

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* Highway Research Board Special Report 80.

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