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16. Abstract

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# TENSILE AND ELASTIC CHARACTERISTICS OF PAVEMENT MATERIALS

by

Bryant P. Marshall
Thomas W. Kennedy

Research Report Number 183-1

Tensile Characterization of Highway Pavement Materials
Research Project 3-9-72-183

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

January 1974

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

# PREFACE

This is the first in a series of reports dealing with the findings of a research project concerned with tensile and elastic characterization of highway pavement materials. This report summarizes the results of a study to determine the tensile and elastic properties (tensile strength, modulus of elasticity, and Poisson's ratio) and the variations that can be expected in these properties for materials actually used in pavements throughout the state of Texas.

This report would not have been possible without the help and assistance of many people. Special appreciation is due Messrs. James N. Anagnos, Pat Hardeman, Victor N. Toth, and Harold H. Dalrymple for their assistance in the testing program, and to Messrs. Avery Smith, Gerald Peck, and James L. Brown, of the Texas Highway Department, who provided technical liaison for the project. Appreciation is extended to the district laboratory engineers who supplied the materials tested in this study. These laboratory engineers were Messrs. David Bass, Charles W. Baxter, Volney G. Chetty, C. R. Doyle, Warren H. Dudley, Weldon R. Gibson, Charles H. Little, Robert E. Long, Billy R. Neeley, W. L. Plumlee, and the late Harrison D. Swilley. Thanks are also extended Mr. A. W. Eatman for his cooperation in this project. Thanks are due the Center for Highway Research staff, who assisted with the manuscript. The support of the Federal Highway Administration, Department of Transportation, is gratefully acknowledged.

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January 1974

## LIST OF REPORTS

Report No. 183-1, "Tensile and Elastic Characteristics of Pavement Materials," by Bryant P. Marshall and Thomas W. Kennedy, summarizes the results of a study on the magnitude of the tensile and elastic properties of highway pavement materials and the variations associated with these properties which might be expected in an actual roadway.

ABSTRACT

This report describes the results of an investigation of the tensile and elastic properties of highway pavement materials. Cores of four types of materials obtained from recently constructed highway pavements were obtained and tested. Experimental estimates of the tensile and elastic properties (tensile strength, modulus of elasticity, and Poisson's ratio) of these materials were made using the indirect tensile test. In addition, the variation in the tensile and elastic properties which can be expected along the design length of a roadway was estimated.

KEY WORDS: tensile strength, modulus of elasticity, Poisson's ratio, variation, highway pavement materials, indirect tensile test.

SUMMARY

This report summarizes the findings of a study conducted to evaluate the tensile and elastic properties of highway pavement materials and the variations in these properties which might be expected along the design length of a roadway. The tensile and elastic properties estimated were tensile strength, modulus of elasticity, and Poisson's ratio. In addition, pavement density and thickness were also analyzed. The test method utilized for this study was the indirect tensile test. Four material types from paving projects throughout the state of Texas were studied: portland cement concrete, cement-treated base, asphaltic concrete, and blackbase.

The average tensile strength and modulus values were 471 psi and $3.99 \times 10^6$ psi for portland cement concrete and 136 psi and $1.09 \times 10^6$ psi for cement-treated base. The average tensile strength, modulus of elasticity, and Poisson's ratio for blackbase were 105 psi, $58.2 \times 10^3$ psi, and 0.27, respectively.

It was found that the magnitude of the variations observed appeared to be material dependent. For tensile strengths the variations were small (coefficients of variation of approximately 20 percent) for concrete; moderate (coefficients ranging from 14 percent to 27 percent) for blackbase and asphaltic concrete; and rather large (coefficients of 23 percent to 49 percent) for cement-treated material. The results also indicated additional variation was introduced along the roadway; however, no definite conclusions could be made without additional investigation involving a better designed core sampling plan. Very little variation (generally less than 3 percent) was encountered in pavement thickness and density, regardless of material type.

## IMPLEMENTATION STATEMENT

The results of this study to determine the tensile and elastic characteristics of highway pavements recently constructed in Texas can be used immediately. Currently, elastic pavement design methods based on elastic theory are being developed for use by the Texas Highway Department. In addition, considerations are being given to including stochastic analyses in these design methods. The results concerning the magnitude of the tensile and elastic characteristics (tensile strength, modulus of elasticity, and Poisson's ratio) can be utilized immediately as inputs into elastic design methods. The information on the variation of the above properties provides an estimate of the variation which occurs in actual pavements. These variation estimates are therefore important and needed for any stochastic design procedures. In addition to the above applications, the districts can use the information to begin to develop a feel for the elastic and tensile properties and the variations of these properties. Such information is needed in order to judge the significance of the values obtained from future tests conducted by the districts and the Materials and Tests Division.

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# CHAPTER 1. INTRODUCTION

Most current pavement design procedures are largely empirical and deterministic in nature, using exact values of input and presenting the results as exact values. At a 1970 workshop on the structural design of asphalt pavements (Ref 1), one of the most pressing areas of research need was established to be the application of probabilistic or stochastic concepts to pavement design. The workshop stated the problem as follows:

> So that designers can better evaluate the reliability of a particular design, it is necessary to develop a procedure that will predict variations in the pavement system response due to statistical variations in the input variables, such as load, environment, pavement geometry, and materials properties including the effects of construction and testing variables. As part of this research, it will be necessary to include a significance study to determine the relative effect on the system response of variations in the different input variables.

Current research at The University of Texas Center for Highway Research has led to design procedures for both rigid pavements (RPS) and flexible pavements (FPS) in which the systems approach is used to consider all phases of design, construction, and in-service performance to arrive at an acceptable pavement design (Refs 2, 3, 4, 5, and 6). Trial use of these design systems by the Texas Highway Department revealed a definite need to consider the random or stochastic nature of many of the input variables so that the design reliability can be estimated. Reliability is defined as "the probability that the pavement will have an adequate serviceability level for a specified design performance period" (Ref 7).

In addition, FPS and RPS are currently in the empirical design stages, and it is felt that the state-of-the-art has advanced to the point where an attempt should be made to apply the theory of elasticity to design (Ref 8). A necessary first step in this direction is the determination of the elastic and tensile properties of pavement materials as they exist in the roadway. Furthermore, the variations in these properties from point to point in the pavement and from different locations in the state must be evaluated in order to fully implement the stochastic design aspects of FPS and RPS.

The purpose of the research effort summarized in this report was to develop information concerning the tensile, deformation, and strength characteristics of pavement materials in the state of Texas and to develop information concerning the variation of these properties in newly constructed pavements in Texas.

Chapter 2 summarizes currently available information concerning the variation of materials characteristics and delineates the need for additional studies. Chapter 3 describes the approach used in this study. Chapter 4 discusses the analysis and findings of the study, and Chapter 5 summarizes the findings and conclusions.

# CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

Based on a review of the literature, it appears that few studies have been conducted to investigate the magnitude and variations of the tensile and elastic properties in highway pavement materials. The lack of information can perhaps be explained by the previous lack of a simple and convenient tensile testing technique to measure these properties. Most current test methods are largely empirical and do not provide information on the elastic parameters. There appears to be limited information on the variation in the elastic properties of field and laboratory prepared specimens and virtually no information on the tensile properties of materials sampled from existing pavements. Research has been conducted at The University of Texas on the tensile properties of laboratory prepared stabilized materials used in highway construction (Refs 9, 10, 11, and 12). There is, however, a considerable amount of data available describing the variation in some of the more routinely determined characteristics of highway paving materials, such as compressive strength, flexural strength, fatigue life, density, slump, air voids, and pavement thickness.

Prior to beginning an investigation of the tensile and elastic properties of pavement materials and their variations, it was felt that the findings of previous investigations should be reviewed and summarized. Previous findings are discussed below and supplemental data are shown in the appendix in Tables A-1 through A-16.

## STUDIES ON LABORATORY PREPARED SPECIMENS

### Concrete

Mitchell (Ref 13), Wright (Ref 14), Addinall (Ref 15), and Hondros (Ref 16) conducted studies to investigate the tensile strength of laboratory prepared concrete and cement mortar specimens using the indirect tensile test. Some of the principal findings concerning variations in tensile properties of these materials are summarized in Table A-1. The results of these tests indicated that coefficients of variation of up to 8 percent can be expected for the tensile strengths of replicate specimens of laboratory prepared concrete.

Hondros (Ref 16) performed a series of tests on 24-inch diameter × 2-inch thick cement mortar disks which were instrumented with strain gages in order to determine values of Poisson's ratio and modulus of elasticity of the test specimens (Table A-2). A coefficient of variation of 12.2 percent was obtained for values of Poisson's ratio, and a coefficient of variation of 6.4 percent was obtained for modulus values, which were of approximately the same magnitude as those for tensile strength in Table A-1.

### Asphalt Cement and Asphaltic Concrete

Finn (Ref 17) reports the variation in laboratory tests of stiffness modulus, fatigue life (fracture life), and initial strain in weathered and unweathered specimens of asphalt cement (Table A-3). The asphalt specimens were weathered in a rolling thin film oven developed by the California Division of Highways. The range of coefficients of variation obtained in the stiffness and initial strain determinations was generally between 7 and 22 percent, with an average value of 17.3 percent, while the coefficient of variation obtained for fatigue life was considerably higher, ranging from 53 to 73 percent, and averaging 62.2 percent.

Vallerga et al (Ref 18) made similar studies on different penetration grade asphalts, both aged and unaged. Their results are comparable to those reported by Finn (Ref 17), with low to moderate variation in stiffness and initial strain and rather high variation in fatigue life.

Moore and Kennedy (Ref 19) investigated the fatigue life of asphalt-treated gravel and limestone materials under repeated indirect tensile stresses. Significant variations in fatigue life occurred, and it was found that the standard deviation tended to vary linearly with mean fatigue life. The coefficient of variation ranged from 30 percent for asphalt-treated limestone to more than 75 percent for asphalt-treated gravel.

## STUDIES ON FIELD SPECIMENS

### Asphaltic Concrete

Finn (Ref 17) summarized work done by Monismith (Ref 20) on the laboratory determined values of beam stiffness for surface and base course specimens of asphaltic concrete obtained from the field. In these tests the average coefficient of variation was 26.2 percent and was approximately the same for both surface and base courses (Table A-4). Also shown in Table A-4, for comparison, are the results of stiffness tests on laboratory compacted replicate specimens of surface and base courses. As expected, the average coefficient of variation for the laboratory compacted specimens was lower than that for the field specimens, averaging 18.5 percent. This value would have been somewhat lower were it not for the relatively high value of 28.2 percent for the laboratory compacted specimens tested at 40° F.

In another study, Monismith et al (Ref 21) obtained field specimens of surface and base courses from an asphalt pavement in California and conducted beam tests for flexural stiffness. A total of 20 surface course specimens and 8 base course specimens were obtained from approximately the same location in the pavement (Table A-5). For a given test temperature, the coefficient of variation was essentially the same for the surface and base courses. For the tests conducted at 68° F, the average coefficient of variation obtained was 27.5 percent, while for those tests run at 40° F, the average coefficient of variation obtained was 20.1 percent.

A great deal of information relating to the variation in material properties encountered on a construction project was gathered during the construction of the AASHO Road Test. It must be pointed out, however, that the AASHO Road Test was not typical of most construction projects in that extreme construction control was exercised, with upper and lower specification limits specified. Both binder courses and asphalt surface courses were tested for each of the six test loops that were built. The results of in-place density tests (Table A-6) on the asphaltic concrete pavement sections indicated that the variation was very small, averaging 1.2 percent, with a range from 0.5 to 1.8 percent. The variation in each loop was comparable to that for all loops combined.

The results of percent voids determinations (percent total volume and percent filled) for the asphaltic concrete pavement are also contained in Table A-6. The average coefficient of variation for the voids (percent total volume) was 11.2 percent for the binder course and 19.3 percent for the surface course. The average coefficient of variation for the voids (percent filled) was 5.6 percent for the binder course and 7.0 percent for the surface course. The coefficients of variation for all six loops combined were not significantly different from those obtained for each of the six individual loops.

Concrete and Cement-Treated Material

The AASHO Road Test (Ref 22) also provided information concerning compacted density and compressive strength for cement-treated base (Table A-7). Coefficients of variation of 2.4 percent for the field in-place density and 14.5 percent for the seven-day compressive strength were obtained.

The results of 14-day compressive and flexural strength tests on concrete beams and cylinders molded from concrete from each of the six loops of the AASHO Road Test (Ref 22) are summarized in Table A-8. Each test for flexural strength represents the average of two breaks on one beam, while each compressive strength test is the average of the strength obtained from each of two cylinders in a set. The variations in the flexural tests and compressive tests were about equal, with an average value of 7.5 percent.

Concrete beams and cylinders were cast during the paving operations on the test tangents for determining flexural and compressive strengths as a function of time. A set of specimens consisting of six beams and 12 cylinders was made every five days of paving for each of the two pavers used in the operation. The concrete for all specimens for any one set was obtained from a single batch. One beam and two cylinders from each set of specimens were tested at each designated age (Table A-9). The variations which were obtained were generally less than 9 percent for the flexural tests and 30 percent for the compressive tests. The average coefficient of variation for the flexural tests was 6.5 percent and the average coefficient of variation for the compressive strength tests was 11.9 percent.

Abdun-Nur considers a realistic picture of concrete produced under normal control to be one in which the coefficient of variation of the 28-day strength is between 20 and 25 percent, while good concrete is concrete with a 15 percent coefficient of variation (Ref 23). Data from a West Virginia Road Commission research report on the variation in 28-day compressive strengths of portland cement paving concrete are shown in Table A-10. Five paving projects are represented, and the coefficients of variation obtained ranged from 9.8 to 16.5 percent, with an average value of 12.9 percent.

An analysis of historical data on compressive strengths of concrete based on a report by the Florida Department of Transportation is shown in Table A-11. Two types of concrete, Class A and Class NS, were studied. Routine control was normally exercised over Class A concrete, while Class NS was only occasionally spot checked. The average coefficient of variation of the 11 Class A concrete projects sampled was 13.1 percent and varied from 8.8 to 14.7 percent. The average coefficient of variation for the Class NS concrete projects, where less control was exercised, was 17.8 percent with a total range of 7.9 percent.

The Louisiana Department of Highways, as part of its quality control research program, studied the variation in thickness of concrete pavements. The variations in thickness were generally below 5 percent, with an average value of approximately 2.8 percent for all three thicknesses sampled (Table A-12).

Variation in pavement thickness was also studied by the state of Oklahoma. The thicknesses were measured by inserting a probe in the plastic concrete. Again, rather small coefficients of variation were obtained, averaging 3.0 percent (Table A-13).

GENERAL DISCUSSION OF THE COMPONENTS OF VARIANCE

In order to arrive at a stage where application of statistical concepts is effective, it is necessary to make estimates of the components of the overall variance measured for a given material. The components of overall variance $\sigma_T^2$ can be isolated into testing variance $\sigma_t^2$, sampling variance $\sigma_s^2$, and inherent material variance $\sigma_a^2$ such that

$$\sigma_T^2 = \sigma_t^2 + \sigma_s^2 + \sigma_a^2$$

In order to determine inherent material variation, it is obvious that the testing and sampling components of variation must be isolated and analyzed.

During the years 1966-1969, the Office of Research and Development of the Bureau of Public Roads actively promoted research programs in quality assurance. Early research revealed that few data were available for use in establishing quality levels and statistical variations in highway construction. As of 1969, 28 states had conducted research along these lines, and, according to data received, in some studies 50 percent or more of the overall variance measured could be assigned to sampling and testing (Ref 24).

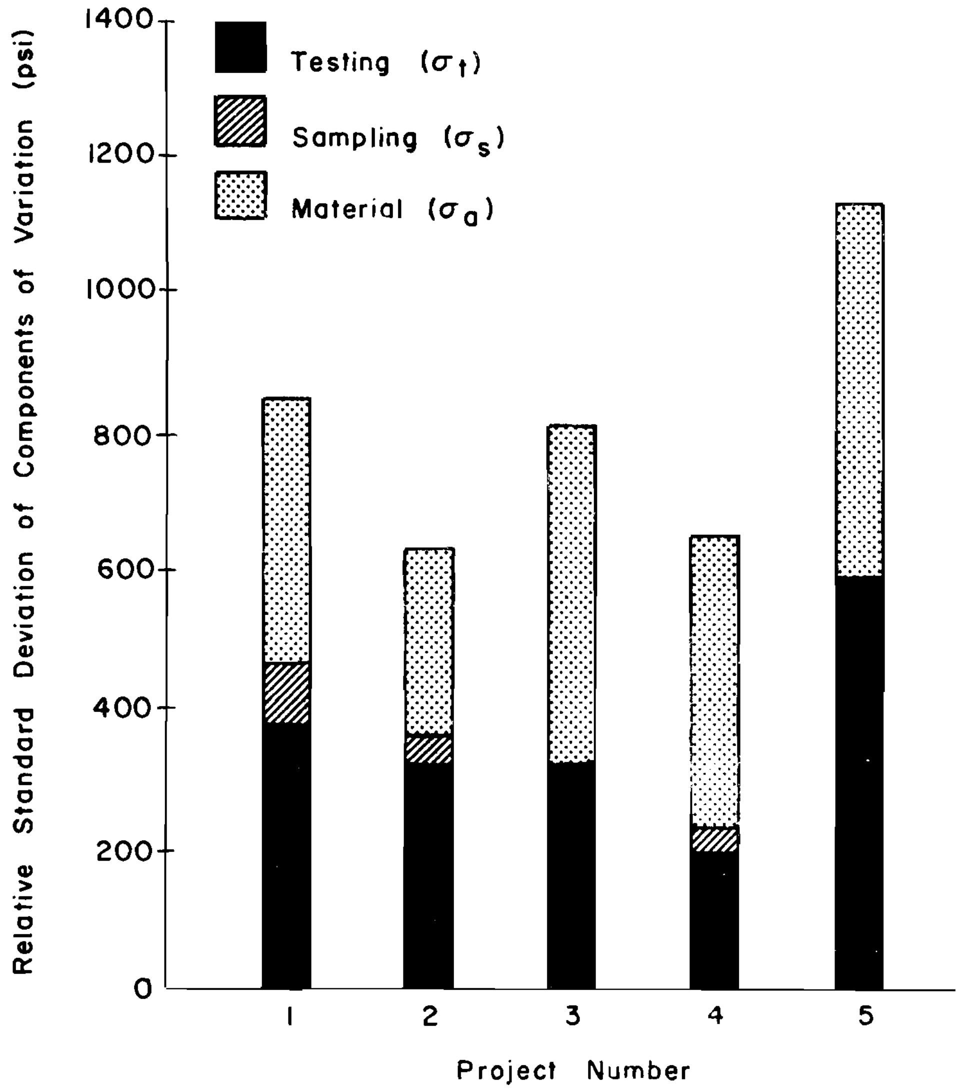
The components in overall variation in 28-day compressive strength of portland cement concrete shown in Table A-10 are analyzed and reported in Table A-14. Figure 1 depicts the relationship among the material, sampling, and testing standard deviations. Since standard deviations are not additive, the sum of the individual standard deviation components for a given project does not equal the overall standard deviation shown in Table A-14. From these data, it was found that the sampling and testing components of variation generally exceeded the inherent material variation component.

Results of studies of concrete consistency by several states, as measured by the slump cone method, indicated that the coefficients of variation for slump range from 21.5 to 53.3 percent (Table A-15). The data seem to indicate that the material variance constitutes a substantial portion of the overall variance in measured consistency.

Neaman and Laguros (Ref 26) conducted a study of the components of variation on a portland cement concrete pavement section approximately 8 miles long as part of a quality control research project. The variation in some of the more pertinent characteristics of the pavement and the components of this variation are contained in Table A-16. Again, rather small variation was found in the thickness of the pavement, with the coefficient of variation being 1.1 percent. Moderate variations were found in air content and cylinder strength, while a rather large coefficient of variation, 53 percent, was found in the slump measurements. The data on the components of the overall variance reveal that the material variance constituted a large portion of the overall variance for the properties reported.

## SUMMARY

Based on a review of the literature, it appears that few studies have been conducted to evaluate the magnitude of the tensile and elastic properties and the variation in these properties for cores of in-place highway pavement materials. More quantitative information regarding the tensile and elastic characterization of these materials is needed. Based on a limited amount of testing, a range of mean values and variations of some of the more routinely determined properties of these materials has been presented.




Note: Scale is Applicable Only to Individual Standard Deviation Components. As Standard Deviations are Not Additive, Overall Standard Deviation Cannot be Read from Scale.

Fig 1. Relationship among variation components for concrete pavement 28-day compressive strength (Ref 25).

Low coefficients of variation (less than 5 percent) were found for measurements of density and thickness. Moderate coefficients of variation, between 10 and 20 percent, were found for flexural stiffness, initial strain, and compressive strength measurements, while coefficients of variation ranging from 20 percent to in excess of 75 percent were found for fatigue life determinations. Studies have indicated that sampling and testing components sometimes constitute a large portion of the overall variation measured.

# CHAPTER 3. EXPERIMENTAL PROGRAM

The principal objectives of this investigation were (1) to characterize highway paving materials in terms of their tensile and elastic properties, specifically tensile strength, Poisson's ratio, and modulus of elasticity; and (2) to establish an estimate of the variation in these properties which can be expected for an in-place pavement but not necessarily to establish the cause of the variation. To accomplish these objectives, field cores of various highway paving materials from construction projects in the state of Texas were tested using the indirect tensile test. Mean values for the tensile and elastic properties were established, and the variation about these mean values was estimated.

Roadway designers have traditionally assumed that the properties of paving material are constant along a design length of roadway, where design length can be defined as a specific length along a roadway which is designed for uniform thickness and materials type. However, it has been shown that even in replicate specimens of material prepared under closely controlled laboratory conditions there is a random variation in properties. This variation as measured in the laboratory represents inherent material variation plus some amount of testing error. Moving from the laboratory environment to a field construction site, it could be expected that more variation would be introduced as a result of the relatively uncontrolled construction process as compared to carefully controlled laboratory conditions.

In order to estimate the additional variation introduced due to the construction process, a set of cores could be obtained from a small area in the pavement and tested. The scatter in test results from this "clustered" sample would be an estimate of the variation introduced by the construction process as well as by the inherent variation of the material and by testing. Additional variation may also be introduced with time during construction. The variation in material properties introduced along the road includes inherent material variation as well as variation introduced by the environment, changes in the constituents of the mix, changes in contractor or construction technique, and various other factors. This "along-the-road" variation could be estimated by testing cores sampled randomly along the design length of the project.

In addition to the variation which occurs horizontally in the pavement, it may be of interest to determine the variation which occurs vertically since the lower portion of a pavement layer is subjected to the highest load-induced tensile stresses. For example, when placing a concrete pavement, it is not uncommon to have segregation of the coarse aggregate toward the bottom of the pavement slab, with cement paste and excess water concentrating near the top, especially if the concrete is overvibrated. In addition, the upper face of the pavement is exposed to the atmosphere, the lower face is exposed to the base material, and the central portion of the slab is unexposed. Consequently, the properties of the concrete may be a function of its relative location or depth in the pavement. Thus, it would be of interest to determine whether there is a difference between the upper and lower portions of the pavement. Also, for blackbase and asphaltic concrete pavements, there may be differences between lifts or layers.

## DESCRIPTION OF PROJECTS TESTED

It was originally anticipated that several different types of pavement material would be available for testing, including portland cement concrete, blackbase, asphaltic concrete, asphalt-treated materials, cement-treated materials, and lime-treated materials. However, due to the lack of newly completed construction projects using some of these materials or the difficulty in obtaining an intact core, only four materials were tested, of which portland cement concrete and blackbase constitute approximately 75 percent, since they are most commonly used in paving projects. Asphaltic concrete and cement-treated base material constituted the remaining 25 percent of the cores tested. A summary of the projects tested is shown in Table 1. Figure 2 shows the geographical distribution of the Highway Department districts from which the pavement cores were obtained.

## CORE SAMPLING PLAN UTILIZED IN THIS STUDY

It was originally planned that a small number of cores would be taken from selected paving projects throughout the state of Texas. However, the

TABLE 1. PROJECTS TESTED

| | Portland Cement Concrete | | | Blackbase | | | Asphaltic Concrete | | | Cement-Treated Base | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| District | Project Ident. | No. Cores | No. Spec. | Project Ident. | No. Cores | No. Spec. | Project Ident. | No. Cores | No. Spec. | Project Ident. | No. Cores | No. Spec. |
| 2 | 2-A | 38 | 104 | 2-A | 38 | 76 | | | | | | |
| | 2-E | 50 | 134 | | | | | | | | | |
| 8 | | | | 8-A | 11 | 16 | | | | | | |
| 12 | 12-Sp | 21 | 46 | | | | | | | 12-Sp | 18 | 32 |
| 13 | 13-Sp | 10 | 28 | 13-A | 11 | 14 | | | | | | |
| | | | | 13-B | 19 | 35 | | | | | | |
| | | | | 13-C | 13 | 16 | | | | | | |
| 15 | | | | 15-A | 27 | 77 | 15-A | 15 | 15 | | | |
| 17 | 17-B | 60 | 170 | 17-B | 50 | 100 | | | | | | |
| | 17-M | 62 | 167 | | | | | | | | | |
| 18 | 18-N | 9 | 25 | 18-B | 6 | 12 | | | | | | |
| | 18-O | 24 | 72 | | | | | | | | | |
| 19 | 19-A | 34 | 72 | 19-A | 22 | 54 | | | | 19-A | 23 | 34 |
| | 19-B | 50 | 105 | 19-B | 18 | 36 | | | | 19-B | 17 | 26 |
| 20 | | | | | | | | | | 20-A | 15 | 29 |
| Total | 10 | | | 10 | | | 1 | | | 4 | | |

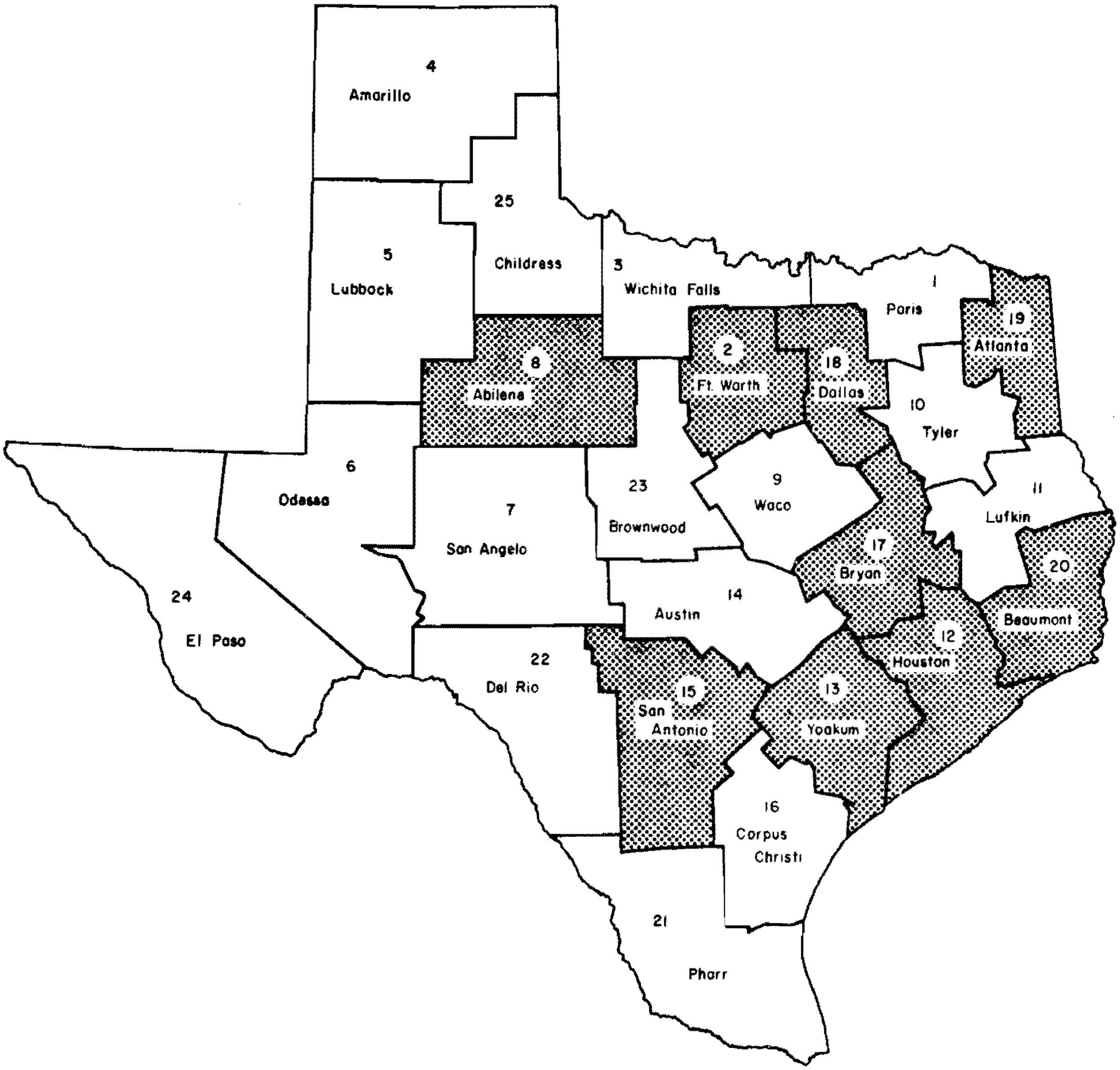



Fig 2. Texas Highway Department Highway Districts from which cores were obtained.

Texas Highway Department routinely cores newly completed pavements in order to determine pavement thickness. Since a large number of cores are taken for that purpose, it was felt that more information could be obtained by testing a relatively large number of these cores than by testing a relatively few cores taken solely for this project. Thus, arrangements were made with Texas Highway Department personnel to obtain cores from recently constructed pavements.

The Highway Department normally cores a portland cement concrete pavement approximately every 1000 feet unless a thin section is encountered, i.e., a section of pavement in which the depth is less than design depth. When this occurs, cores are taken at 10-foot intervals from a fixed location on the pavement relative to the center line until the depth again reaches design depth, at which time cores are again taken at 1000-foot intervals (Fig 3). The core sampling plan used for pavements other than concrete depends on the policy of each district.

When this concept of systematic random sampling is used, the Highway Department cores can be considered to have been randomly sampled from the pavement. This concept assumes that samples obtained in a systematic fashion (e.g., at 1000-foot intervals) can be considered to be random when the sampling function does not coincide with any variation distribution function that may exist in the pavement.

As previously discussed, one method of estimating the additional variation due to construction would be to test cores clustered at approximately the same location in the pavement. Considered with the total length of a project, a group of cores obtained at 10-foot intervals approximates a cluster, and is the most economical approach possible for most projects.

The variation introduced during construction (along-the-road variation) as a result of changes in pit source, weather, etc. can be estimated with the cores obtained at large distance intervals (e.g., 1000 feet for concrete pavements).

## SPECIMEN PREPARATION

All portland cement concrete cores were obtained with a 4-inch-inside-diameter core barrel from 8-inch or 9-inch nominal depth pavements. Since many projects involved a large number of cores, and due to time restrictions, not all cores could be tested. Therefore, a portion of the cores were selected at random to represent the along-the-road sample and, where present, the

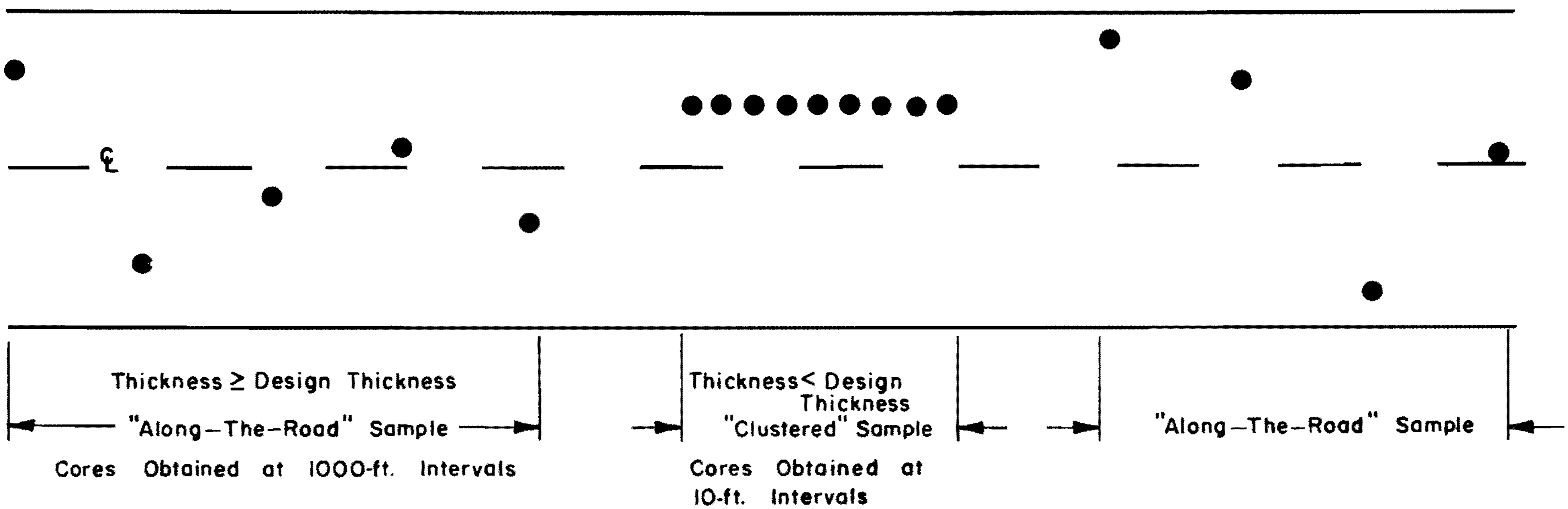



Fig 3. Typical core sampling plan used by the Texas Highway Department for concrete pavements.

clustered sample for a given project. The remaining cores were saved for a future study of the fatigue characteristics of highway paving materials. The concrete paving projects were typically multilane roadways in which the two main directional lanes (i.e., northbound and southbound) were treated as separate roadways for sampling purposes.

To investigate differences with respect to depth in the pavement, normally three specimens were cut from each concrete core, one from the top, center, and bottom of the core, although it was not always possible to obtain a specimen from the center of the concrete cores due to the presence of reinforcing steel. Each specimen was approximately 2 inches thick, with a 4-inch diameter.

Both 4-inch and 6-inch-diameter blackbase cores were tested. The cores were sawed at the interface between lifts whenever possible, so that each specimen represented only one lift.

Before the specimen was tested, its dimensions were accurately measured and the specimen was weighed so that its density could be estimated.

## GENERAL DESCRIPTION OF INDIRECT TENSILE TEST

The tensile and elastic properties of the paving materials studied were estimated using the indirect tensile test procedure as modified slightly (Ref 12) from that originally recommended by Hudson and Kennedy (Ref 27). The indirect tensile test involves loading a cylindrical specimen with compressive loads which act parallel to and along the vertical diametral plane, as shown in Fig 4. To distribute the load and maintain a constant loading area, the compressive load is applied through a half-inch-wide steel loading strip which is curved at the interface with the specimen and has a radius of curvature equal to the radius of the specimen.

The loading configuration shown in Fig 4 develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane which ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter (Fig 5). By measuring the applied load at failure and by continuously monitoring the loads and the horizontal and vertical deformations of the specimen, it is possible to estimate the tensile strength, Poisson's ratio, and modulus of elasticity of the specimen.

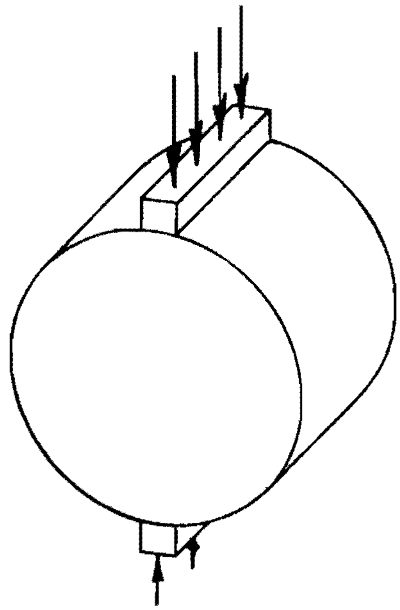


Fig 4. Cylindrical specimen with compressive load being applied.

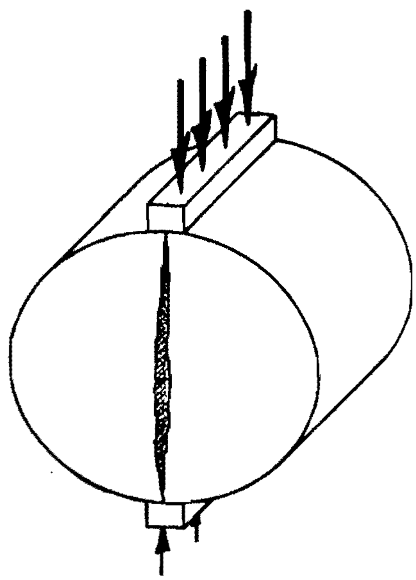


Fig 5. Specimen failing in tension under compressive load.

TEST EQUIPMENT AND PROCEDURE

The basic test equipment used in this study was the same as that previously used in studies on stabilized materials at the Center for Highway Research, The University of Texas at Austin (Refs 9, 10, 11, and 12). The basic testing apparatus includes a loading system and a means of monitoring the applied loads, the horizontal deformation of the specimen, and the vertical deformation of the specimen.

The loading system consisted of an MTS loading system, a loading device, and loading strips. In this study, a closed loop electrohydraulic system was used in order to accurately control the deformation rate. For the tests conducted in this study, a deformation rate of 0.5 inch per minute was used for tests on portland cement concrete and cement-treated materials and a rate of 2 inches per minute was used on blackbase and asphaltic concrete. All tests were conducted at a temperature of approximately 75° F.

It was necessary to use a special loading device to insure that the loading platens and strips remain parallel during the test. A loading device which has proven to be satisfactory and which was used in this study is a modified, commercially available die set with upper and lower platens constrained to remain parallel during the test (Fig 6). Mounted on the upper and lower platens are half-inch-wide curved steel loading strips.

The load was monitored with a load cell in order to obtain electrical readouts which could be recorded continuously. Horizontal deformations of the specimen were measured using a device basically consisting of two cantilevered arms with strain gages attached (Fig 7). Vertical deformations were measured with a DC linear-variable-differential transformer (LVDT). This LVDT was also used to control the vertical deformation rate during the test by providing an electrical signal relative to the movement between the upper and lower platens. The loads and deformations were monitored by two X-Y plotters, one recording load and horizontal deformation, and one recording load and vertical deformation.

Points picked from the X-Y plots were used as input for computer program MODLAS 9, which was developed at the Center for Highway Research at The University of Texas to calculate the tensile and elastic properties of materials tested using the indirect tensile test. Included in the printed output are estimates of Poisson's ratio, modulus of elasticity, tensile strength, and density for each specimen tested.

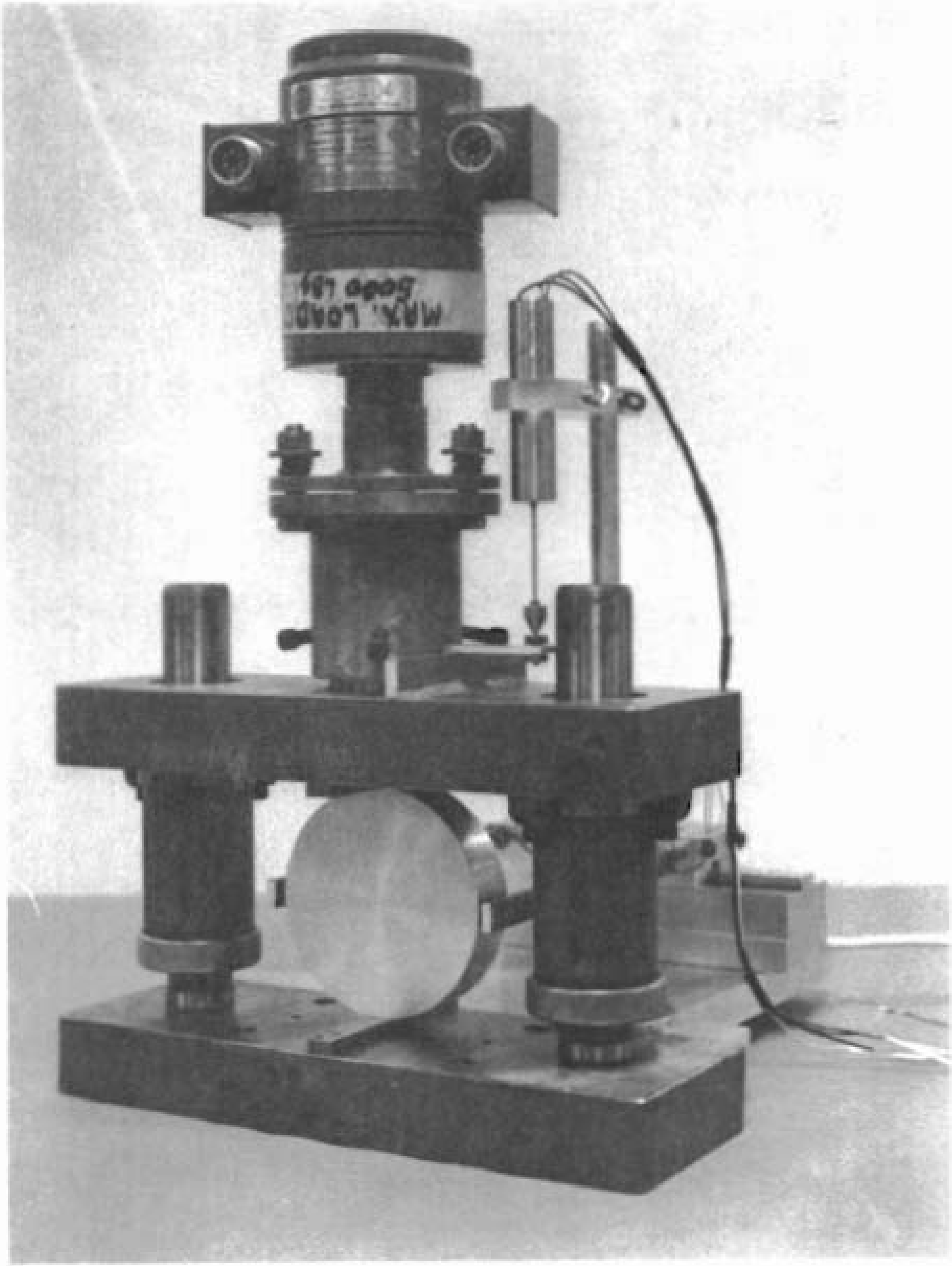


Fig 6. Indirect tensile test equipment in test mode.

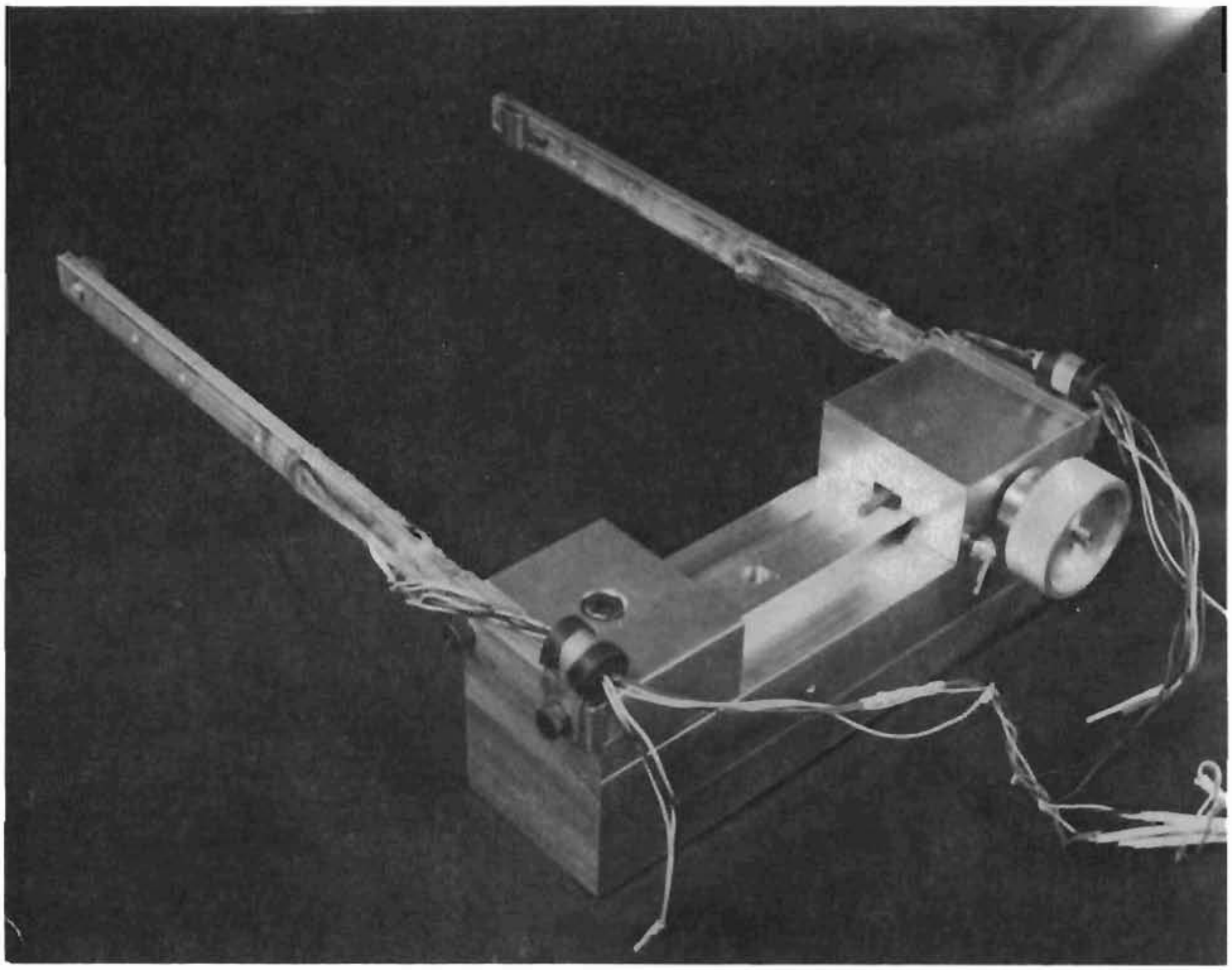


Fig 7. Horizontal deformation measuring device.

The modulus of elasticity calculated in MODLAS 9 for the concrete and cement-stabilized materials was based on an estimated value of Poisson's ratio, since total vertical deformations of these materials at failure are very small, and since surface irregularities cause a significant error in the vertical deformation measurement which precludes the experimental determination of Poisson's ratio. An estimated value of 0.20 for concrete and 0.22 for cement-treated materials was used. Since the true Poisson's ratio may have been different from the assumed value, which would have affected the calculated modulus value, a sensitivity analysis was conducted to determine the magnitude of the effect on computed modulus produced by changes in Poisson's ratio. A range of Poisson's ratio values from 0.18 to 0.24 was used for concrete and a range from 0.20 to 0.26 was used for cement-treated base.

No experimental difficulties were encountered in the tests on blackbase and asphaltic concrete; consequently Poisson's ratio was experimentally estimated, and the modulus value for each specimen was calculated using the experimentally determined Poisson's ratio value.

## METHOD OF ANALYSIS

One of the objectives of this study was to obtain an estimate of the variation in material properties existing in a highway pavement. For this purpose, the coefficient of variation was defined as the sample standard deviation divided by the sample mean, expressed as a percent.

In order for the coefficient of variation to be a valid and meaningful test statistic, it must be assumed that the material property being analyzed is approximately normally distributed about some mean value. Studies have shown that the variability of highway materials and properties follows common statistical distributions, such as the normal distribution (Refs 8 and 28), and, therefore, this assumption should be reasonably valid.

# CHAPTER 4. ANALYSIS AND EVALUATION OF TEST RESULTS

The primary objective of this study was to synthesize information on the elastic and tensile characteristics and their variations for various highway pavement materials in order to provide preliminary estimates of materials properties for the design of pavements. The materials tested and evaluated for this purpose were portland cement concrete (PCC), blackbase (BB), asphaltic concrete (HMAC), and cement-treated base (CTB), and for convenience and ease of discussion, the results for each material are discussed separately.

## PORTLAND CEMENT CONCRETE

Cores were obtained from a total of ten projects from six Texas Highway Department districts. Three of these projects had clustered samples involving cores obtained at 10-foot intervals. Each core was generally sawed to obtain three specimens. Each of these specimens was tested using the indirect tensile test, and the test results were used to estimate tensile strength and modulus of elasticity. In addition, the variation in pavement thickness was determined for the projects for which this information was available and densities were estimated by measuring the dimensions and weight of the specimens. A summary of the test results is shown in Tables 2 through 4. Aggregate type is shown in Table 2.

### Tensile Strength

The results of tests involving the individual specimens, regardless of whether the specimen was cut from the top, center, or bottom of the core, are summarized in Table 2. Mean tensile strength values varied from 391 psi to 584 psi and averaged 471 psi. The coefficient of variation for the mean tensile strength values for each project was 13 percent, and, while this value was not large, it did indicate that there were differences between projects, which means that the coefficients of the individual projects are more meaningful than an overall coefficient. Coefficients of variation within given projects were very consistent at about 20 percent. This magnitude of variation is

TABLE 2. SUMMARY OF TEST RESULTS FOR INDIVIDUAL ALONG-THE-ROAD SPECIMENS [1], PCC PAVEMENT PROJECTS

| District | Project Identification | Aggregate Type | Number of Specimens | Distance Covered (miles) | Tensile Strength | | Modulus of Elasticity [2] | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean (psi) | CV (%) | Mean ($10^6$ psi) | CV (%) | Mean (pcf) | CV (%) |
| 2 | 2-A | Limestone | 104 | 17.0 | 459 | 19 | 4.14 | 40 | 140.6 | 1.1 |
| | 2-E | Limestone | 134 | 27.3 | 490 | 20 | 3.70 | 35 | 140.1 | 1.6 |
| 12 | 12-Sp | Gravel | 46 | - | 466 | 29 | 3.66 | 36 | 138.5 | 4.7 |
| 13 | 13-Sp | Gravel | 28 | - | 584 | 19 | 4.38 | 22 | 140.7 | 1.7 |
| 17 | 17-B | Gravel | 141 | 23.3 | 498 | 19 | 5.02 | 26 | 142.4 | 2.0 |
| | 17-M | Gravel | 122 | 22.0 | 428 | 20 | 3.62 | 37 | 141.3 | 1.4 |
| 18 | 18-N | Limestone | 25 | 4.6 | 424 | 19 | 3.74 | 24 | 142.0 | 1.8 |
| | 18-O | Limestone | 72 | 4.2 | 566 | 19 | 4.24 | 26 | 146.2 | 1.2 |
| 19 | 19-A | Gravel | 72 | 16.1 | 427 | 21 | 3.36 | 42 | 140.9 | 1.5 |
| | 19-B | Iron ore, slag, gravel | 63 | 12.9 | 391 | 20 | 3.40 | 42 | 133.1 | 1.9 |
| | | | Weighted Average | | 471 | 20 | 3.99 | 34 | - | 1.7 |
| | | | Range | | 193 | 10 | 1.66 | 20 | - | 3.6 |
| | | | CV of Means (%) | | 13 | | 13 | | - | |

[1] Top, center, and bottom slices from each core.

[2] Assumed Poisson's ratio = 0.20.

comparable to that found for flexural and compressive strength in previous studies.

A comparison of the strengths of the top, center, and bottom specimens indicated that there was a general increase in strength with depth (Table 3). However, only the specimens cut from the bottom of the cores had significantly higher tensile strengths than the specimens from the top and center portions of the cores. These strength differences ranged from 20 to as much as 150 psi, and were significant at a 95 percent confidence level. The strengths of the center and top specimens were not significantly different from each other. Thus, a portion of the within-project variation shown in Table 2 can be attributed to the variation due to location or position within the core.

Modulus of Elasticity

Since reliable estimates of Poisson's ratio for concrete could not be obtained experimentally, it was necessary to assume a value of Poisson's ratio in order to calculate a modulus. The value assumed was 0.20. Results of a sensitivity analysis (Table 5) indicate that a 25 percent change in Poisson's ratio (0.18 to 0.24) produced a 12 percent change in the computed modulus value ($3.58 \times 10^6$ to $4.06 \times 10^6$ psi). The coefficient of variation, however, was constant.

Comparison of the top, center, and bottom specimens from each core revealed that in most cases there was an increase in modulus with depth and that the bottom specimens generally had a higher modulus than the centers and tops. Even though this difference was significant at a probability level of 0.95, the trend was not as pronounced as that for tensile strength. As with strength comparisons, there were generally no significant differences between center and top specimens.

From Table 2 it can be seen that the range in mean modulus values for the ten projects tested was not large. The values for all ten projects ranged from $3.36 \times 10^6$ psi to $5.02 \times 10^6$ psi and averaged $3.99 \times 10^6$ psi. The coefficient of variation of the mean modulus values from Table 2 was 13 percent, which is approximately the same as for strength. The variation in modulus within a given project was low to moderate, with coefficients of variation ranging from 22 percent to 42 percent. The average coefficient for all ten projects was 34 percent.

TABLE 3. TENSILE STRENGTH AND MODULUS OF TOP, CENTER, AND BOTTOM SPECIMENS FROM CONCRETE CORES

| District | Project Identification | Number of Specimens | | | Tensile Strength (psi) | | | Modulus of Elasticity (psi × $10^6$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | T | C | B | Tops | Centers | Bottoms | Tops | Centers | Bottoms |
| 2 | 2-A | 35 | 31 | 38 | 438 | 453 | 484 | 4.12 | 3.78 | 4.48 |
| | 2-E | 47 | 39 | 48 | 466 | 464 | 535 | 3.78 | 3.62 | 3.70 |
| 12 | 12-Sp | 16 | 13 | 15 | 497 | 485 | 428 | 4.03 | 3.95 | 3.24 |
| 13 | 13-Sp | 9 | 9 | 10 | 530 | 586 | 630 | 3.96 | 4.59 | 4.55 |
| 17 | 17-B | 43 | 49 | 49 | 455 | 477 | 557 | 4.67 | 4.95 | 5.39 |
| | 17-M | 42 | 38 | 42 | 397 | 432 | 455 | 3.33 | 3.45 | 4.06 |
| 18 | 18-N | 9 | 7 | 9 | 406 | 422 | 442 | 3.43 | 3.93 | 3.90 |
| | 18-O | 24 | 24 | 24 | 516 | 545 | 636 | 3.59 | 4.13 | 5.02 |
| 19 | 19-A | 29 | 14 | 29 | 404 | 446 | 440 | 3.27 | 3.57 | 3.35 |
| | 19-B | 28 | 8 | 27 | 390 | 374 | 398 | 3.47 | 2.96 | 3.47 |
| Weighted Average | | | | | 443 | 469 | 502 | 3.80 | 3.99 | 4.20 |

TABLE 4. CLUSTERED AND ALONG-THE-ROAD TEST RESULTS FOR PCC PAVEMENT PROJECTS

| District | Project Identification | Sample Plan | Number of Specimens | Distance Covered | Tensile Strength | | Modulus of Elasticity [1] | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean (psi) | CV (%) | Mean ($10^6$ psi) | CV (%) | Mean (pcf) | CV (%) |
| 17 | 17-B | ATR | 141 | 23.3 miles | 498 | 19 | 5.02 | 26 | 142.4 | 2.0 |
| | | Cluster | 29 | 150 feet | 476 | 22 | 5.00 | 31 | 144.3 | 0.8 |
| 17 | 17-M | ATR | 122 | 22.0 miles | 428 | 20 | 3.62 | 37 | 141.3 | 1.4 |
| | | Cluster 1 | 21 | 240 feet | 416 | 18 | 3.84 | 37 | 141.2 | 1.2 |
| | | Cluster 2 | 24 | 200 feet | 447 | 21 | 3.84 | 37 | 141.3 | 1.1 |
| 19 | 19-B | ATR | 63 | 12.9 miles | 391 | 20 | 3.40 | 42 | 133.1 | 1.9 |
| | | Cluster 1 | 25 | 90 feet | 415 | 15 | 3.22 | 42 | 134.5 | 1.6 |
| | | Cluster 2 | 17 | 100 feet | 436 | 19 | 3.40 | 40 | 135.0 | 1.6 |

[1] Assumed Poisson's ratio = 0.20.

TABLE 5. SENSITIVITY OF MODULUS OF ELASTICITY TO ASSUMED POISSON'S RATIO FOR PORTLAND CEMENT CONCRETE [1] AND CEMENT-TREATED MATERIAL [2]

| Assumed Poisson's Ratio | Modulus of Elasticity | | | | | |
|---|---|---|---|---|---|---|
| | Portland Cement Concrete | | | Cement-Treated Material | | |
| | Mean ($10^6$ psi) | SD ($10^6$ psi) | CV (%) | Mean ($10^6$ psi) | SD ($10^6$ psi) | CV (%) |
| 0.18 | 3.58 | 0.86 | 24 | - | - | - |
| 0.20 | 3.74 | 0.90 | 24 | 0.578 | 0.344 | 60 |
| 0.22 | 3.90 | 0.94 | 24 | 0.602 | 0.358 | 60 |
| 0.24 | 4.06 | 0.97 | 24 | 0.627 | 0.373 | 60 |
| 0.26 | - | - | - | 0.652 | 0.388 | 60 |

For Portland Cement Concrete:

$$\frac{0.24 - 0.18}{0.24} = \text{25\% change in Poisson's Ratio}$$

Results in

$$\frac{4.06 - 3.58}{4.06} = \text{12\% change in Elasticity}$$

For Cement-Treated Material:

$$\frac{0.26 - 0.20}{0.26} = \text{23\% change in Poisson's Ratio}$$

Results in

$$\frac{0.652 - 0.578}{0.652} = \text{11\% change in Elasticity}$$

[1] 25 specimens

[2] 29 specimens

### Density and Pavement Thickness

Project densities ranged from 133.1 pcf to 146.2 pcf. Coefficients of variation were generally very small, averaging 1.7 percent. Pavement thickness measurements shown in Table 6 indicate minimal variation. Coefficients of variation were generally less than 3 percent for the 8-inch design depth pavements. The depth variation for the one project with a 9-inch design depth was somewhat greater, with a coefficient of variation of 4.7 percent.

The magnitudes of these variations are consistent with values reported from previous studies which indicated low coefficients of variation for pavement thickness and density.

### Clustered Sample Analysis

As seen in Table 4, the mean modulus and tensile strength values and coefficients of variation for the clustered samples are not significantly different from those of the along-the-road samples for the same project, although the clustered samples were expected to have a smaller variation. Thus, it would seem that for the projects evaluated no significant additional variations were introduced along the roadway or that the longitudinal distances covered by the clustered samples, which ranged from 90 to 240 feet, were sufficiently large to allow variation other than that inherent to the material and method of construction to be introduced. In fact, in some instances the cluster variation exceeds the along-the-road variation, probably due to the large differences in sample size.

## CEMENT-TREATED BASE

A summary of the results from tests on cement-treated materials is shown in Table 7. Specimens from four projects in three districts were tested. The results tend to demonstrate that an obvious characteristic of this material is its highly variable nature.

### Tensile Strength

Mean tensile strengths ranged from 83 psi to 210 psi; however, when the results of one project were excepted, the range was 83 psi to 120 psi. The high strength, 210 psi, was due to the high cement content used and, in fact, this material might appropriately be classified as a lean concrete. The significant difference between projects was indicated by the high coefficient

TABLE 6. THICKNESS OF PORTLAND CEMENT CONCRETE PAVEMENTS [1]

| District | Project Identi-fication | Sample Plan | Number of Cores | Pavement Thickness | | |
|---|---|---|---|---|---|---|
| | | | | Mean (inches) | CV (%) | Design (inches) |
| 2 | 2-A | ATR [2] | 38 | 8.3 | 2.6 | 8.0 |
| | 2-E | ATR | 50 | 8.3 | 2.5 | 8.0 |
| 17 | 17-B | ATR | 50 | 8.2 | 2.6 | 8.0 |
| | | Cluster [3] | 10 | 7.8 | 1.2 | 8.0 |
| | 17-M | ATR | 47 | 8.2 | 2.6 | 8.0 |
| | | Cluster 1 | 7 | 7.7 | 1.0 | 8.0 |
| | | Cluster 2 | 8 | 7.6 | 1.1 | 8.0 |
| 18 | 18-N | ATR | 9 | 8.8 | 3.7 | 8.0 |
| | 18-O | ATR | 24 | 9.5 | 4.7 | 9.0 |
| 19 | 19-A | ATR | 34 | 8.2 | 2.9 | 8.0 |
| | 19-B | ATR | 31 | 8.2 | 3.4 | 8.0 |
| | | Cluster 1 | 10 | 7.6 | 0.6 | 8.0 |
| | | Cluster 2 | 9 | 7.6 | 1.4 | 8.0 |

[1] Thickness determined by measuring depth of core in laboratory.

[2] Along-the-road.

[3] Cluster samples from thin section where thickness is less than design value.

TABLE 7. SUMMARY OF ALONG-THE-ROAD TEST RESULTS, CEMENT-TREATED BASE[1] PROJECTS

| District | Project Identi-fication | Type of Material | Number of Specimens | Distance Covered (miles) | Tensile Strength Mean (psi) | Tensile Strength CV (%) | Modulus of Elasticity[2] Mean ($10^6$ psi) | Modulus of Elasticity[2] CV (%) | Density Mean (pcf) | Density CV (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 12-A | Sand shell | 32 | - | 210 | 31 | 1.76 | 72 | 128.4 | 3.9 |
| 19 | 19-A | Soil cement | 20 | 1.4 | 90 | 23 | 1.05 | 83 | 122.0 | 1.9 |
| | 19-B | Soil cement | 19 | 1.2 | 83 | 37 | 0.73 | 57 | 121.3 | 2.8 |
| 20 | 20-A | Burned clay | 29 | 1.5 | 120 | 49 | 0.60 | 60 | 113.8 | 3.7 |
| | | | Weighted Average | | 136 | 36 | 1.09 | 68 | - | 3.2 |
| | | | Range | | 127 | 26 | 1.16 | 26 | - | 2.0 |
| | | | CV of Means (%) | | 46 | - | 50 | - | - | - |

[1] Results for all individual specimens or lifts.

[2] Assumed Poisson's ratio = 0.22.

of variation of the means, 46 percent. The coefficients of variation within each project were moderate to high, ranging from 23 percent to 49 percent.

Modulus of Elasticity

Since experimental estimates of Poisson's ratio for cement-treated bases could not be obtained experimentally, a Poisson's ratio of 0.22 was assumed. Results of the sensitivity analysis (Table 5) indicate that a 23 percent change in Poisson's ratio (0.20 to 0.26) produced an 11 percent change in the computed modulus value ($0.578 \times 10^6$ psi to $0.652 \times 10^6$ psi). The coefficient of variation, however, was not affected.

As seen in Table 7, mean modulus values varied from $0.60 \times 10^6$ psi to $1.76 \times 10^6$ psi, and averaged $1.09 \times 10^6$ psi. Excluding the high modulus material, the average modulus was $0.77 \times 10^6$ psi and the range was from $0.60 \times 10^6$ to $1.05 \times 10^6$ psi. The variation for the individual projects was moderate to high, with coefficient of variation values ranging from 57 percent to 83 percent, and averaging 68 percent.

Density

Densities were subject to much less variation than either tensile strength or modulus. Coefficients of variation for density ranged from 1.9 percent to 3.9 percent, and averaged approximately 3.2 percent, which, as previously noted, is comparable to that found in previous studies.

Clustered Sample Analysis

It can be seen in Table 8 that the coefficients of variation for the clustered samples were lower than those for the along-the-road samples, indicating that additional variation was probably introduced. However, the mean values for the clustered samples were also lower, which cannot be explained.

General

Variations within projects and among projects are rather large when compared to those obtained in tests on concrete. This is possibly explained by the fact that most cement-treated jobs are commonly field mixed with in-situ soils, which are sometimes highly variable. This is also a relatively crude process when compared to batch plant mixing. However, two of the cement-treated projects, sand-shell from District 12 and the burned clay from District 20, were batch plant mixed, and it can be seen from Table 7 that

TABLE 8. CLUSTERED AND ALONG-THE-ROAD TEST RESULTS FOR CEMENT-TREATED BASE

| District | Project Identi-fication | Sample Plan | Number of Specimens | Distance Covered | Tensile Strength | | Modulus of Elasticity [1] | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean (psi) | CV (%) | Mean ($10^5$ psi) | CV (%) | Mean (pcf) | CV (%) |
| 19 | 19-A | ATR | 20 | 1.4 miles | 90 | 23 | 10.54 | 83 | 122.0 | 1.9 |
| | | Cluster 1 | 7 | 1 foot | 66 | 57 | 4.54 | 57 | 116.3 | 1.7 |
| | | Cluster 2 | 7 | 1 foot | 85 | 24 | 8.28 | 66 | 119.1 | 3.3 |
| 19 | 19-B | ATR | 19 | 1.2 miles | 83 | 37 | 7.34 | 57 | 121.3 | 2.8 |
| | | Cluster | 7 | 1 foot | 58 | 18 | 4.70 | 48 | 119.4 | 1.5 |

[1] Assumed Poisson's ratio = 0.22.

large variations also existed for modulus and tensile strength. It is believed that the highly variable nature of both aggregates and the relative nonhomogeneity of the mix contributed to the variation. In order to partially compensate for this large variation, high cement contents were used with the sand-shell which increased the mean tensile strength and modulus values well above minimum design values.

BLACKBASE

A description of the ten blackbase projects is contained in Table 9. Summaries of the test results for the projects are shown in Tables 10 and 11; only two of the projects had clustered samples. The parameters estimated using the indirect tensile test were tensile strength, modulus of elasticity, and Poisson's ratio. Density was estimated by measuring the dimensions and weights of the specimens.

Tensile Strength

The mean tensile strengths for the various projects ranged from 53 psi to 157 psi and averaged 102 psi. The lower extreme value, however, was from Project 13, which produced very rough cores which were difficult to test and which may have produced low strength values. Eliminating Project 13, the tensile strengths ranged from 84 to 157 with an average of 105 psi.

In addition to the fact that the various blackbase materials were composed of different aggregates and asphalts and had different strengths, as indicated by the coefficient of variation of the means (27 percent with Project 13 and 23 percent without Project 13), the various projects also had different coefficients of variation. Thus, the coefficients for the individual projects are more meaningful than the overall coefficient of variation for all specimens. These coefficients ranged from 14 percent to 40 percent and averaged 26 percent for all projects. By eliminating Project 13, which exhibited larger variations, the range was 14 to 27 percent, with an average of 21 percent.

Many of these specimens were obtained from the same core by sawing specimens from the individual lifts. Since these lifts were placed at different times, these specimens can be considered to be independent of each other. On the other hand, the properties of the material in the lifts at any given location determine the behavioral characteristics of the pavement at that location.

TABLE 9. DESCRIPTION OF BLACKBASE PROJECTS

| District | Project Identification | Number of Cores | Number of Specimens | Distance Covered (miles) | Asphalt | | Aggregate |
|---|---|---|---|---|---|---|---|
| | | | | | Type | % by wt. | |
| 2 | 2-A | 38 | 76 | 15.0 | AC-20 | 5.5 | Crushed limestone, field sand |
| 8 | 8-A | 11 | 16 | 3.3 | AC-20 | 5.5-6.2 | Crushed limestone, sand, gravel |
| 13 | 13-A | 11 | 14 | 8.0 | AC-20 | 4.2 | Pit-run gravel |
| | 13-B | 19 | 28 | 4.3 | AC-20 | 4.0-4.9 | |
| | 13-C | 13 | 16 | 3.0 | AC-20 | 4.0-4.4 | |
| 15 | 15-A | 27 | 49 | 10.9 | AC-10 | 5.1 | Pit-run gravel |
| 17 | 17-B | 50 | 100 | 19.1 | AC-10<br>AC-20 | 4 | Brazos River gravel |
| 18 | 18-B | 6 | 12 | 0.9 | AC-20 | 5.5-6.5 | Pea gravel, field sand |
| 19 | 19-A | 22 | 54 | 19.3 | AC-20 | 4.8-5.6 | Gravel, crushed slag, sand |
| | 19-B | 18 | 36 | 15.2 | AC-20 | 4.3-6.4 | |

TABLE 10. SUMMARY OF ALONG-THE-ROAD TEST RESULTS FOR INDIVIDUAL SPECIMENS, BLACKBASE PROJECTS

| District | Project Identification | Number of Specimens | Distance Covered (miles) | Tensile Strength | | Modulus of Elasticity | | Poisson's Ratio | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean (psi) | CV (%) | Mean ($10^3$ psi) | CV (%) | Mean | CV (%) | Mean (pcf) | CV (%) |
| 2 | 2-A | 76 | 15.0 | 84 | 20 | 38.6 | 32 | 0.34 | 39 | 127.0 | 2.4 |
| 8 | 8-A | 16 | 3.3 | 112 | 14 | 91.5 | 29 | 0.28 | 40 | 138.4 | 2.6 |
| 13 | 13-A | 14 | 8.0 | 87 | 40 | 44.9 | 46 | 0.16 | 58 | * | * |
| | 13-B | 28 | 4.3 | 104 | 36 | 87.3 | 62 | 0.16 | 73 | * | * |
| | 13-C | 16 | 3.0 | 53 | 40 | 35.0 | 40 | 0.26 | 57 | * | * |
| 15 | 15-A | 49 | 10.9 | 157 | 17 | 86.1 | 59 | 0.23 | 47 | 140.4 | 2.2 |
| 17 | 17-B | 100 | 19.1 | 105 | 27 | 55.2 | 44 | 0.24 | 41 | 136.0 | 2.3 |
| 18 | 18-B | 12 | 0.9 | 107 | 25 | 42.2 | 24 | 0.20 | 64 | 135.1 | 2.3 |
| 19 | 19-A | 54 | 19.3 | 95 | 20 | 55.2 | 33 | 0.32 | 38 | 141.6 | 1.7 |
| | 19-B | 36 | 15.2 | 88 | 21 | 64.7 | 34 | 0.16 | 67 | 136.1 | 3.6 |
| | | Weighted Average | | 102 | 26 | 58.8 | 40 | 0.25 | 52 | - | - |
| | | Range | | 104 | 26 | 56.5 | 38 | 0.18 | 35 | - | - |
| | | CV of Means (%) | | 27 | - | 36 | - | 28 | - | - | - |
| | | EXCLUDING PROJECT 13 | | | | | | | | | |
| | | Weighted Average | | 105 | 21 | 58.2 | 36 | 0.27 | 48 | - | 2.4 |
| | | Range | | 73 | 13 | 52.9 | 35 | 0.18 | 29 | - | 1.9 |
| | | CV of Means (%) | | 23 | - | 33 | - | 25 | - | - | - |

*Not attainable

TABLE 11. CLUSTERED AND ALONG-THE-ROAD TEST RESULTS FOR BLACKBASE SPECIMENS

| District | Project Identification | Sample Plan | Number of Specimens | Distance Covered | Tensile Strength | | Modulus of Elasticity | | Poisson's Ratio | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean (psi) | CV (%) | Mean ($10^3$ psi) | CV (%) | Mean | CV (%) | Mean (pcf) | CV (%) |
| 13 | 13-B | ATR | 28 | 4.3 miles | 104 | 36 | 87.3 | 62 | 0.16 | 73 | - | - |
| | | Cluster 1 | 4 | 50 feet | 133 | 11 | 72.4 | 31 | 0.11 | 36 | - | - |
| | | Cluster 2 | 3 | 50 feet | 173 | 7 | 67.5 | 8 | 0.18 | 37 | - | - |
| 15 | 15-A | ATR | 49 | 10.9 miles | 157 | 17 | 86.1 | 59 | 0.23 | 47 | 140.4 | 2.2 |
| | | Cluster 1 | 7 | 250 feet | 146 | 11 | 73.2 | 42 | 0.21 | 44 | 141.7 | 1.2 |
| | | Cluster 2 | 6 | 250 feet | 151 | 18 | 71.6 | 36 | 0.31 | 41 | 140.2 | 2.9 |
| | | Cluster 3 | 7 | 250 feet | 159 | 9 | 75.8 | 20 | 0.33 | 24 | 142.0 | 0.8 |

Thus, a comparison was made to determine whether there were strength differences between layers.

This comparison indicated that there was no significant difference in the tensile strength of the specimens from the various layers at a confidence level of 95 percent.

Modulus of Elasticity

Mean modulus values (Table 10) varied from $35.0 \times 10^3$ psi to $91.5 \times 10^3$ psi and averaged $58.8 \times 10^3$ psi. The coefficient of variation of the mean modulus values was 36 percent, indicating project differences. Elimination of Project 13 did not significantly change these values, $38.6 \times 10^3$ to $91.5 \times 10^3$, with an average of $58.2 \times 10^3$ psi. Coefficients of variation within projects ranged from 24 percent to 62 percent and averaged 40 percent. Eliminating Project 13, the coefficients ranged from 24 percent to 59 percent and the average was reduced to 36 percent.

A comparison of the moduli of the layers comprising a given core indicated no significant differences existed between layers at a confidence level of 95 percent.

Poisson's Ratio

Mean Poisson's ratio values (Table 10) ranged from 0.16 to 0.34, with an average of 0.25 with Project 13 and 0.27 without Project 13. The coefficient of variation of these means was 25 percent, which was approximately the same magnitude as the coefficient obtained for strength. The variation in Poisson's ratio for each project was found to be large, ranging from 39 percent to 73 percent, with an average of 52 percent. With the elimination of Project 13, the range was 39 percent to 67 percent and the average was reduced to 48 percent. This large range of coefficients is probably due to the fact that the calculation of Poisson's ratio is very sensitive to small errors in the deformation measurements.

Density

A comparison of the mean densities for each project (Table 10) has no meaning since different aggregates were used. The coefficients of variation of the densities for each project were generally small, ranging from 1.7 to 3.6 and averaging 2.4 percent. The magnitudes of these variations are consistent with values reported from previous studies, which indicated low coefficients of variation for density.

### Clustered Sample Analysis

Table 11 contains the results of the analysis of the clustered samples for the two projects which had cores for analysis.

The coefficients of variation (Table 11) for tensile strength, modulus of elasticity, and Poisson's ratio for the clustered samples were somewhat smaller than for the along-the-road samples, indicating that additional variation was introduced by along-the-road changes. However, because of the limited number of projects, no definite conclusions could be made.

## ASPHALTIC CONCRETE

Only one asphaltic concrete project was tested, and the results are summarized in Table 12. The mean values for tensile strength, modulus of elasticity, and Poisson's ratio were 77 psi, $42.0 \times 10^3$ psi, and 0.40, respectively. The coefficients of variation for the same properties were 16 percent, 29 percent, and 27 percent, respectively. These values were generally smaller than those obtained for blackbase, possibly indicating greater design and construction control. However, additional projects should be tested before definite conclusions are made. As with the other materials, the variation in densities was small, 3.7 percent, for a mean density of 133.5 pcf.

TABLE 12. SUMMARY OF ALONG-THE-ROAD TEST RESULTS, ASPHALTIC CONCRETE [1]

| District | Project Identi- fication | Number of Specimens | Distance Covered (miles) | Tensile Strength | | Modulus of Elasticity | | Poisson's Ratio | | Density | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean (psi) | CV (%) | Mean ($10^3$ psi) | CV (%) | Mean | CV (%) | Mean (pcf) | CV (%) |
| 15 | 15-A | 15 | 10.9 | 77 | 16 | 42.0 | 29 | 0.40 | 27 | 133.5 | 3.7 |

[1] Results for all individual specimens or lifts.

# CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the findings of a study to determine the magnitude of the tensile and elastic properties of pavement material and the variations associated with these properties for use in an elastic pavement design procedure incorporating stochastic and reliability concepts. Cores from newly constructed pavements were obtained and tested using the indirect tensile test in order to obtain estimates of tensile strength, Poisson's ratio, and modulus of elasticity, and the variations in these properties which might be expected in a highway pavement. No attempt was made to determine the cause of observed differences. The pavement materials examined included portland cement concrete (ten projects), blackbase (ten projects), cement-treated base (four projects) and asphaltic concrete (one project). The conclusions and recommendations based on the findings of this study are stated below.

## CONCLUSIONS

### GENERAL

(1) Based on the fact that the projects tested were different, as evidenced by the variation in mean values from project to project for a given material type, it was concluded that the coefficients of variation obtained for individual projects are more meaningful than an overall coefficient for all projects.

(2) Very little variation (generally less than 3 percent) was encountered in pavement thickness and density, regardless of material type.

(3) Results of the clustered sample analyses tend to indicate that additional variation is introduced along the roadway, but no definite conclusions can be made without additional investigation involving more carefully designed core sampling plan to obtain clustered samples.

(4) The magnitude of the variations observed appeared to depend on the material involved. Relatively small variations were found for portland cement concrete, moderate variations were associated with blackbase and asphaltic concrete, and large variations were found to exist in cement-treated materials.

## PORTLAND CEMENT CONCRETE

### Tensile Strength

(1) Mean tensile strengths varied from 391 psi to 584 psi and averaged 471 psi.

(2) Tensile strength tended to increase with increasing pavement depth, i.e., the tensile strength of the concrete from the bottom of the pavement slab was higher than that of concrete taken from the center or top of the slab.

(3) The within-project coefficient of variation was approximately the same for all projects, regardless of the mean value.

(4) The coefficient of variation for each project was approximately 20 percent for individual specimens.

### Modulus of Elasticity

(1) Mean modulus values for all specimens varied from $3.36 \times 10^6$ psi to $5.02 \times 10^6$ psi and averaged $3.99 \times 10^6$ psi.

(2) As with tensile strength, the modulus tended to increase with increasing depth, with the concrete at the bottom of the pavement having a higher modulus than that from the center or top of the pavement.

(3) The within-project coefficient of variation ranged from 22 percent to 42 percent and averaged 34 percent for individual specimens.

## CEMENT-TREATED BASE

### Tensile Strength

(1) Mean tensile strengths varied from 83 psi to 120 psi, with one project with a high cement content (District 12) producing a strength of 210 psi.

(2) The within-project coefficients of variation were moderate to high, ranging from 23 percent to 49 percent and averaging 36 percent.

### Modulus of Elasticity

(1) Mean modulus values varied from $.60 \times 10^6$ psi to $1.76 \times 10^6$ psi. Excluding the high modulus material, the average modulus was $0.77 \times 10^6$ psi.

(2) The within-project coefficients of variation were moderate to high, ranging from 57 percent to 83 percent and averaging 68 percent.

BLACKBASE

Tensile Strength

(1) Mean tensile strength values varied from 84 psi to 157 psi and averaged 105 psi. The coefficient of variation of the mean values was 23 percent.

(2) No significant differences in tensile strength were found to exist between the various layers or lifts at a confidence level of 95 percent.

(3) The within-project coefficients of variation were moderate for individual specimens, ranging from 14 percent to 27 percent and averaging 21 percent.

Modulus of Elasticity

(1) Mean modulus values varied from $38.6 \times 10^3$ psi to $91.5 \times 10^3$ psi and averaged $58.2 \times 10^3$ psi. The coefficient of variation of the mean modulus values was 33 percent, which is slightly higher than that for tensile strength.

(2) No significant differences in modulus of elasticity were found to exist between the various layers or lifts at a confidence level of 95 percent.

(3) Coefficients of variation for each project ranged from 24 percent to 59 percent and averaged 36 percent.

Poisson's Ratio

(1) Mean Poisson's ratio values ranged from 0.16 to 0.34 and averaged 0.27. The coefficient of variation of the mean values was 25 percent, which was approximately equal to that obtained for both strength and modulus.

(2) Within-project variation for each project was large, ranging from 39 percent to 67 percent and averaging 49 percent.

(3) Trends similar to those observed for tensile strength and modulus were observed in the reduction of variation when average core values were analyzed.

ASPHALTIC CONCRETE

(1) The mean values for tensile strength, modulus of elasticity, and Poisson's ratio for one project were 77 psi, $42.0 \times 10^3$ psi, and 0.40, respectively.

(2) The coefficients of variation for tensile strength, modulus of elasticity, and Poisson's ratio were 16 percent, 29 percent, and 27 percent, respectively, which were generally smaller than those obtained for blackbase.

(3) No conclusions could be reached since only one project was involved.

## RECOMMENDATIONS

(1) Since only a limited variety of materials was available for this study, it is recommended that additional material types be obtained and tested to supplement the results of this study. These should include lime-treated materials, if possible, and additional cement-treated materials and asphaltic concrete.

(2) The materials tested in this study were obtained from newly completed pavements. Thus, a future study should involve obtaining and testing additional cores from the projects tested in this study to evaluate the time effects of age, traffic loadings, and climatic changes.

(3) Future research should be directed toward the fatigue characterization of field cores of highway paving materials, i.e., the behavior of the materials when subjected to dynamic or repeated loadings such as those imposed by moving wheel loads on a highway pavement. The fatigue characterization should include the magnitude of the fatigue life as well as the variations associated with fatigue life.

(4) Additional research should be conducted to investigate the effect of repeated applications of load on the tensile and elastic properties of paving materials.

(5) The information obtained from this study on the magnitude of and variation in the tensile and elastic properties of pavement materials should be used as in the development of stochastic pavement design procedure based on elastic thoery.

(6) The Texas Highway Department should utilize the indirect tensile test to begin to develop additional information on the tensile characteristics of pavement materials being used in the state. The district laboratories should concentrate on using the test to determine strength and to evaluate the strength values in terms of the performance characteristics of pavements. The

Materials and Tests Division (D-9) should also conduct the test for strength but, in addition, should attempt to estimate and evaluate modulus of elasticity and Poisson's ratio.

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# APPENDIX

## SUPPLEMENTAL DATA -- CURRENT STATUS OF KNOWLEDGE

TABLE A-1. VARIATION IN INDIRECT TENSILE STRENGTHS OF LABORATORY PREPARED SPECIMENS

| Reference | Number of Tests | Specimen Size | Material | Average Indirect Tensile Strength (psi) | CV (%) | Comments |
|---|---|---|---|---|---|---|
| 13 | 24 | 3-in. dia. x 6-in. cylinders | Keene's cement | 226 | 6.0 | Tested one day after casting |
| 14 | 32 | 6-in. dia. x 12-in. cylinders | Concrete | 405 | 5.0 | Rate of tensile stress application was 100 psi/minute |
| 15 | 5 | 4-in. dia. x 1-in. disks | Plaster | 445 | 6.0 | Flat steel loading platens, no cushion |
| 15 | 5 | 4-in. dia. x 1-in. disks | Plaster | 563 | 8.0 | Flat steel loading platens with cardboard cushions |
| 16 | 16 | 6-in. dia. x 12-in. cylinders | Concrete | 266 | 4.5 | 28-day strengths, plywood loading strips |
| 16 | 16 | 24-in. dia. x 2-in. disks | Concrete | 295 | 6.0 | 28-day strengths, plywood loading strips |

TABLE A-2. VARIATION IN ELASTIC PROPERTIES OF CEMENT MORTAR DISK USING THE INDIRECT TENSILE TEST (Ref 16)

| Number of Tests | Specimen Size | Mean | Standard Deviation | CV (%) | Mean | Standard Deviation | CV (%) |
|---|---|---|---|---|---|---|---|
| 16 | 24-in. dia. x 2-in. disks instrumented with strain gages | 0.196 | 0.024 | 12.2 | 4.22 | 0.27 | 6.4 |

TABLE A-3. VARIATION IN FATIGUE LIFE, INITIAL STRAIN, AND FLEXURAL STIFFNESS OF WEATHERED AND UNWEATHERED ASPHALT CEMENT AT 68° F (Ref 17)

| Specimen Description | Stress (psi) | No. of Spec. | Fatigue Life (cycles) Mean | Fatigue Life (cycles) Std. Dev. | Fatigue Life (cycles) Coeff. of Var. (%) | Initial Strain (in./in. x $10^{-6}$) Mean | Initial Strain (in./in. x $10^{-6}$) Std. Dev. | Initial Strain (in./in. x $10^{-6}$) Coeff. of Var. (%) | Stiffness (psi) Mean | Stiffness (psi) Std. Dev. | Stiffness (psi) Coeff. of Var. (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unweathered | 200 | 4 | 6,474 | 4,909 | 75.8 | 972 | 200 | 20.6 | 213,000 | 44,600 | 20.9 |
| asphalt | 150 | 4 | 17,997 | 11,438 | 63.6 | 717 | 88 | 12.3 | 200,000 | 42,800 | 21.4 |
| | 90 | 4 | 363,025 | 194,385 | 53.5 | 431 | 77 | 17.8 | 211,000 | 39,400 | 18.6 |
| Weathered | 375 | 4 | 1,665 | 1,108 | 66.5 | 662 | 109 | 16.4 | 582,000 | 112,000 | 19.2 |
| asphalt | 280 | 4 | 16,172 | 9,238 | 57.1 | 464 | 106 | 22.8 | 624,000 | 131,000 | 20.9 |
| | 120 | 3 [1] | 252,926 | 142,348 | 56.3 | 253 | 24 | 9.5 | 476,000 | 34,000 | 7.2 |

[1] Test of fourth specimen discontinued after approximately 70,000 cycles of loading.

TABLE A-4. FLEXURAL STIFFNESS MEASUREMENTS ON FIELD SAMPLES OF ASPHALTIC CONCRETE USING PULSE LOADING METHOD (Ref 17)

| | | Measured Stiffness (psi x $10^5$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 68° F | | | 40° F | | |
| Sample Group | No. of Spec-imens | Mean | Std. Dev. | CV (%) | Mean | Std. Dev. | CV (%) |
| Specimens From Surface Course | | | | | | | |
| 1 | 19 | 1.79 | 0.42 | 23.5 | 6.80 | 1.53 | 22.5 |
| 2 | 20 | 1.65 | 0.39 | 23.6 | 7.03 | 1.91 | 27.2 |
| 3 | 20 | 1.52 | 0.41 | 26.9 | 7.12 | 1.41 | 19.8 |
| 4 | 19 | 1.34 | 0.37 | 27.6 | 5.90 | 1.11 | 18.8 |
| Lab compacted | 26 | 1.29 | 0.22 | 17.0 | 5.76 | 0.74 | 12.8 |
| Specimens From Base Course | | | | | | | |
| 1 | 12 | 1.57 | 0.42 | 26.6 | 5.95 | 1.54 | 25.9 |
| 2 | 12 | 1.39 | 0.26 | 18.7 | 5.66 | 3.14 | 55.5 |
| 3 | 8 | 1.47 | 0.41 | 27.9 | 4.40 | 0.90 | 20.4 |
| 4 | 10 | 1.42 | 0.42 | 29.6 | 4.96 | 1.22 | 24.6 |
| Lab compacted | 29 | 1.19 | 0.19 | 16.0 | 5.31 | 1.50 | 28.2 |

TABLE A-5. FLEXURAL STIFFNESS MEASUREMENTS ON PAVEMENT SAMPLES FROM STA 308 + 10 (Ref 21)

| | | Measured Stiffness (psi x $10^5$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 68° F | | | 40° F | | |
| Location | No. of Specimens | Mean | Standard Deviation | CV (%) | Mean | Standard Deviation | CV (%) |
| Surface course | 20 | 1.52 | 0.41 | 27.0 | 7.12 | 1.41 | 19.8 |
| Base course | 8 | 1.47 | 0.41 | 27.9 | 4.40 | 0.90 | 20.4 |

TABLE A-6. ASPHALTIC CONCRETE COMPACTION DATA FROM AASHO ROAD TEST (Ref 22)

| Lab. Data | Field Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Density (pcf) | | | Voids (% tot. vol.) | | | Voids (% filled) | | |
| Loop | No. Tests | Mean | Std. Dev. | CV (%) | Mean | Std. Dev. | CV (%) | Mean | Std. Dev. | CV (%) |
| | | | | | Binder Course | | | | | |
| 1 | 64 | 148.7 | 1.45 | 1.0 | 7.84 | 0.87 | 11.1 | 55.8 | 3.16 | 5.7 |
| 2 | 12 | 148.6 | 0.67 | 0.5 | 7.92 | 0.42 | 5.3 | 55.3 | 1.43 | 2.6 |
| 3 | 86 | 148.5 | 1.52 | 1.0 | 7.90 | 0.94 | 11.9 | 55.6 | 3.48 | 6.3 |
| 4 | 128 | 149.5 | 1.49 | 1.0 | 7.31 | 0.87 | 11.9 | 58.0 | 3.35 | 5.8 |
| 5 | 128 | 148.5 | 1.38 | 0.9 | 8.02 | 0.88 | 11.0 | 54.9 | 3.24 | 5.9 |
| 6 | 192 | 149.3 | 1.77 | 1.2 | 7.46 | 1.09 | 14.6 | 57.2 | 3.84 | 6.7 |
| All | 609 | 149.0 | 1.60 | 1.1 | 7.66 | 0.99 | 12.9 | 56.5 | 3.49 | 6.2 |
| | | | | | Surface Course | | | | | |
| 1 | 64 | 144.4 | 2.52 | 1.8 | 8.00 | 1.61 | 20.1 | 60.4 | 4.89 | 8.1 |
| 2 | 44 | 145.3 | 2.41 | 1.7 | 7.58 | 1.52 | 20.1 | 61.2 | 4.88 | 8.0 |
| 3 | 84 | 147.4 | 2.33 | 1.6 | 6.32 | 1.43 | 22.6 | 66.1 | 5.36 | 8.1 |
| 4 | 84 | 147.8 | 1.70 | 1.2 | 5.68 | 1.05 | 18.5 | 69.0 | 4.15 | 6.0 |
| 5 | 84 | 146.7 | 1.92 | 1.3 | 6.60 | 1.09 | 16.5 | 64.9 | 3.87 | 6.0 |
| 6 | 84 | 148.2 | 1.31 | 0.9 | 5.76 | 0.82 | 14.2 | 67.7 | 3.18 | 4.7 |
| All | 443 | 146.8 | 2.40 | 1.6 | 6.51 | 1.49 | 22.9 | 65.4 | 5.29 | 8.1 |

TABLE A-7. SUMMARY OF DENSITY AND COMPRESSIVE STRENGTH DATA FOR CEMENT-TREATED BASE FROM AASHO ROAD TEST (Ref 22)

| Item | No. Tests or Samples | Mean | Standard Deviation | CV (%) |
|---|---|---|---|---|
| Field in-place density: [1] | | | | |
| Moisture content (%) | 65 | 6.8 | 0.6 | 8.9 |
| Dry density (pcf) | 65 | 138.4 | 3.3 | 2.4 |
| Compressive strength, 7-day (psi) | 35 | 840.0 | 122.0 | 14.5 |

[1] AASHO Designation: T147-54, except rubber balloon apparatus was used to measure volume of hole.

TABLE A-8. SUMMARY OF TEST RESULTS OF HARDENED CONCRETE FROM AASHO ROAD TEST (Ref 22)

| Loop | Flexural Strength[1], 14 Days | | | | Compressive Strength[2], 14 Days | | | |
|---|---|---|---|---|---|---|---|---|
| | No. Tests | Mean (psi) | Std. Dev. (psi) | CV (%) | No. Tests | Mean (psi) | Std. Dev. (psi) | CV (%) |
| $2\frac{1}{2}$-In. Maximum Size Aggregate | | | | | | | | |
| 1 | 16 | 637 | 46 | 7.2 | 8 | 3599 | 290 | 8.1 |
| 2 | 20 | 648 | 37 | 5.7 | 9 | 3603 | 281 | 7.8 |
| 3 | 71 | 630 | 44 | 7.0 | 38 | 3723 | 301 | 8.1 |
| 4 | 96 | 651 | 38 | 5.8 | 48 | 4062 | 288 | 7.1 |
| 5 | 96 | 629 | 28 | 4.4 | 48 | 4196 | 388 | 9.2 |
| 6 | 99 | 628 | 51 | 8.1 | 48 | 3963 | 325 | 8.2 |
| All | 398 | 636 | 45 | 7.1 | 199 | 3966 | 376 | 9.5 |
| $1\frac{1}{2}$-In. Maximum Size Aggregate | | | | | | | | |
| 1 | 4 | 676 | 65 | 9.6 | 2 | 4088 | 162 | 4.0 |
| 2 | 39 | 668 | 44 | 6.6 | 19 | 4046 | 295 | 7.3 |
| 3 | 24 | 667 | 47 | 7.0 | 14 | 3933 | 440 | 11.2 |
| All | 67 | 668 | 46 | 6.9 | 35 | 4004 | 352 | 8.8 |

[1] Average of two breaks on one beam.

[2] Average of two specimens.

TABLE A-9. SUMMARY OF STRENGTH TESTS ON CONCRETE FROM AASHO ROAD TEST (Ref 22)

| Age at Testing | Flexural Strength[1] | | | | Compressive Strength[2] | | | |
|---|---|---|---|---|---|---|---|---|
| | No. Tests | Mean (psi) | Std. Dev. (psi) | CV (%) | No. Tests | Mean (psi) | Std. Dev. (psi) | CV (%) |
| **2½-In. Maximum Size Aggregate** | | | | | | | | |
| 3 days | 11 | 510 | 23 | 4.5 | 11 | 2670 | 784 | 29.4 |
| 7 days | 11 | 620 | 34 | 5.5 | 11 | 3560 | 396 | 11.1 |
| 21 days | 11 | 660 | 51 | 7.7 | 11 | 4130 | 397 | 9.6 |
| 3 months | 11 | 770 | 66 | 8.6 | 11 | 4680 | 487 | 10.4 |
| 1 year | 11 | 790 | 61 | 7.7 | 11 | 5580 | 509 | 9.1 |
| 2 years | 11 | 787 | 66 | 8.4 | 11 | 5818 | 328 | 5.6 |
| **1½-In. Maximum Size Aggregate** | | | | | | | | |
| 3 days | 12 | 550 | 37 | 6.7 | 12 | 2860 | 809 | 28.3 |
| 7 days | 12 | 630 | 35 | 5.6 | 12 | 3780 | 289 | 7.6 |
| 21 days | 12 | 710 | 53 | 7.5 | 12 | 4250 | 365 | 8.6 |
| 3 months | 12 | 830 | 41 | 4.9 | 12 | 4930 | 528 | 10.7 |
| 1 year | 10 | 880 | 53 | 6.0 | 12 | 5990 | 379 | 6.3 |
| 2 years | 12 | 873 | 48 | 5.5 | 12 | 6155 | 373 | 6.1 |

[1]Average of two breaks on one beam.

[2]Average of two specimens.

TABLE A-10. VARIATION IN 28-DAY COMPRESSIVE STRENGTH OF PORTLAND CEMENT CONCRETE PAVEMENT (Ref 24)

| Project Number | Mean (psi) | Standard Deviation (psi) | Coefficient of Variation (%) |
|---|---|---|---|
| 1 | 4,675 | 545 | 11.7 |
| 2 | 3,755 | 420 | 11.2 |
| 3 | 3,720 | 575 | 15.5 |
| 4 | 4,760 | 467 | 9.8 |
| 5 | 4,688 | 733 | 16.5 |
| Average | 4,320 | | 12.9 |

TABLE A-11. HISTORICAL DATA ON CONCRETE COMPRESSIVE STRENGTH (Ref 24)

| Project Number | Number of Samples | Mean (psi) | Overall Std. Dev. (psi) | Coefficient of Variation (%) | Testing Error (psi) |
|---|---|---|---|---|---|
| 28-Day Cylinders--Class A Concrete | | | | | |
| 1[1] | 536 | 4,524 | 396 | 8.8 | 175 |
| 2 | 292 | 4,881 | 540 | 11.1 | 207 |
| 3 | 96 | 5,686 | 544 | 9.6 | 185 |
| 4 | 192 | 5,527 | 566 | 10.2 | 155 |
| 5 | 196 | 5,098 | 577 | 11.3 | 48[2] |
| 6 | 112 | 4,826 | 608 | 12.6 | 196 |
| 7 | 258 | 5,469 | 667 | 12.2 | 150 |
| 8 | 320 | 5,244 | 674 | 12.9 | 158 |
| 9 | 232 | 5,289 | 711 | 13.4 | 192 |
| 10 | 176 | 4,927 | 725 | 14.7 | 210 |
| 11 | 126 | 5,067 | 732 | 14.4 | 162 |
| Average [3] | 230 | 5,140 | 613 | 13.1 | 179 |
| Range | 224 | 860 | 192 | 5.1 | 60 |
| 28-Day Cylinders--Class NS Concrete | | | | | |
| 1[1] | 50 | 4,021 | 398 | 9.9 | 115 |
| 2 | 340 | 3,555 | 550 | 15.5 | 93 |
| 3 | 240 | 4,006 | 580 | 14.5 | 134 |
| 4 | 200 | 3,474 | 605 | 17.4 | 122 |
| 5 | 240 | 3,781 | 670 | 17.7 | 96 |
| 6 | 196 | 4,192 | 729 | 17.4 | 160 |
| 7 | 148 | 4,213 | 733 | 17.4 | 92 |
| 8 | 94 | 4,239 | 774 | 18.3 | 87 |
| 9 | 108 | 3,657 | 774 | 21.2 | 116 |
| 10 | 182 | 3,674 | 776 | 21.1 | 113 |
| 11 | 156 | 4,110 | 776 | 18.9 | 70 |
| 12 | 224 | 4,179 | 825 | 19.8 | 127 |
| 13 | 138 | 3,941 | 884 | 22.4 | 161 |
| Average [3] | 178 | 3,926 | 698 | 17.8 | 114 |
| Range | 246 | 765 | 334 | 7.9 | 91 |

[1] Values not included in range calculations.
[2] Statistical outlier--not included in calculation of range or average.
[3] Averages are not weighted and include all values except the outlier.

TABLE A-12. SUMMARY OF STATISTICAL RESULTS ON THICKNESS OF CONCRETE PAVEMENT (Ref 24)

| Project Number | Number of Samples | Mean (inches) | Variance (inches) | Standard Deviation (inches) | CV (%) |
|---|---|---|---|---|---|
| | | 8-In. Uniform Thickness | | | |
| 1 | 34 | 8.66 | 0.192 | 0.435 | 5.0 |
| 2 | 39 | 8.42 | 0.171 | 0.415 | 4.9 |
| 3 | 48 | 8.35 | 0.040 | 0.200 | 2.4 |
| 4 | 58 | 8.36 | 0.077 | 0.276 | 3.3 |
| 5 | 61 | 8.05 | 0.035 | 0.185 | 2.3 |
| 6 | 66 | 8.11 | 0.089 | 0.300 | 3.7 |
| 7 | 73 | 8.06 | 0.112 | 0.333 | 4.1 |
| Pooled values | -- | 8.29 | 0.088 | 0.300 | 3.6 |
| | | 9-In. Uniform Thickness | | | |
| 1 | 35 | 9.25 | 0.046 | 0.210 | 2.3 |
| 2 | 51 | 9.19 | 0.121 | 0.350 | 3.8 |
| 3 | 58 | 9.28 | 0.048 | 0.220 | 2.4 |
| 4 | 65 | 9.18 | 0.060 | 0.240 | 2.6 |
| 5 | 74 | 9.20 | 0.185 | 0.430 | 4.7 |
| 6 | 88 | 9.11 | 0.029 | 0.170 | 1.9 |
| Pooled values | -- | 9.20 | 0.083 | 0.290 | 3.1 |
| | | 10-In. Uniform Thickness | | | |
| 1 | 64 | 10.38 | 0.061 | 0.240 | 2.3 |
| 2 | 124 | 10.34 | 0.079 | 0.280 | 2.7 |
| 3 | 132 | 10.35 | 0.079 | 0.230 | 2.2 |
| 4 | 141 | 10.28 | 0.083 | 0.290 | 2.8 |
| Pooled values | --- | 10.34 | 0.069 | 0.270 | 2.6 |

TABLE A-13. VARIATION IN PAVEMENT THICKNESS, PROBE METHOD (Ref 23)

| Project Number | Number of Obser-vations | Mean (inches) | Standard Deviation (inches) | Specifi-cation (inches) | CV (%) |
|---|---|---|---|---|---|
| 1 | 72 | 8.5 | 0.3 | 8.0 | 3.5 |
| 2 | 95 | 8.9 | 0.1 | 9.0 | 1.1 |
| 3 | 100 | 9.0 | 0.4 | 9.0 | 4.4 |

TABLE A-14. OVERALL VARIATION AND COMPONENTS IN 28-DAY COMPRESSIVE STRENGTH OF PCC (Ref 24)

| Project Number | Mean (psi) | Overall Std. Dev. $\sigma_T$ (psi) | Overall Coefficient of Variation (%) | Std. Dev., Testing $\sigma_t$ (psi) | Coefficient of Variation, Testing (%) | Std. Dev., Sampling $\sigma_s$ (psi) | Coefficient of Variation, Sampling (%) | Std. Dev., Materials $\sigma_a$ (psi) | Coefficient of Variation, Materials (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4,675 | 545 | 11.7 | 377 | 8.1 | 91 | 0 | 386 | 8.3 |
| 2 | 3,755 | 420 | 11.2 | 322 | 8.5 | 42 | 0 | 270 | 7.1 |
| 3 | 3,720 | 575 | 15.5 | 318 | 8.5 | -- | 0 | 495 | 13.3 |
| 4 | 4,760 | 467 | 9.8 | 200 | 4.2 | 34 | 0 | 420 | 8.8 |
| 5 | 4,688 | 733 | 16.5 | 585 | 12.5 | -- | 0 | 545 | 11.7 |
| Average | 4,320 | | 12.9 | | | | | | |

TABLE A-15. VARIABILITY IN CONCRETE CONSISTENCY, SLUMP CONE METHOD (Ref 24)

| Project Number | Number of Observations | Testing Variance $\sigma_t^2$ (inches) | Sampling Variance $\sigma_s^2$ (inches) | Sampling Variance $\sigma_a^2$ (inches) | Overall Std. Dev. $\sigma_T$ (inches) | Mean (inches) | CV (%) |
|---|---|---|---|---|---|---|---|
| State 1 | | | | | | | |
| 1 [1] | 184 | 0.16 | 0.04 | 0.26 | 0.68 | 2.44 | 27.8 |
| 2 [2] | 200 | 0.13 | 0.02 | 0.45 | 0.80 | 1.50 | 53.3 |
| 3 [2] | 300 | 0.25 | 0.09 | 0.46 | 0.89 | 2.76 | 32.2 |
| State 2 | | | | | | | |
| 1 [3] | 216 | 0.074 | 0.00 | 0.15 | 0.47 | 2.04 | 23.0 |
| 2 [4] | 200 | 0.06 | 0.06 | 0.37 | 0.70 | 1.86 | 37.6 |
| 3 [3] | 200 | 0.08 | 0.025 | 0.42 | 0.73 | 2.34 | 31.2 |
| 4 [5] | 200 | 0.027 | 0.012 | 0.206 | 0.495 | 1.77 | 27.9 |
| 5 [5] | 204 | 0.066 | 0.03 | 0.305 | 0.633 | 2.37 | 26.7 |
| 6 [6] | 200 | 0.033 | 0.034 | 0.14 | 0.456 | 2.12 | 21.5 |
| 7 [7] | 200 | 0.084 | 0.086 | 0.20 | 0.609 | 2.41 | 25.2 |
| 8 | 200 | 0.158 | 0.047 | 0.50 | 0.844 | 2.26 | 37.3 |

[1] Pavement concrete, truck mix.
[2] Pavement concrete, truck mix, slipform.
[3] Pavement concrete, central mix, screw spreader.
[4] Concrete base, central mix, slide spreader.
[5] Structural concrete, truck mix.
[6] Pavement concrete, central mix, slipform.
[7] Pavement concrete, E-34 paver.

TABLE A-16. VARIANCE COMPONENTS FOR PCC PAVEMENT (Ref 26)

| Characteristics | Number of Observations | Testing Variance $\sigma_t^2$ | Sampling Variance $\sigma_s^2$ | Material Variance $\sigma_a^2$ | Overall Variance $\sigma_T^2$ | Overall Std. Dev. $\sigma_T$ | Arithmetic Mean | CV (%) |
|---|---|---|---|---|---|---|---|---|
| | | | | Pavement | | | | |
| Thickness (in.) | 95 | | | | | 0.1 | 8.9 | 1.1 |
| | | | | Plastic Concrete | | | | |
| Slump (in.) | 200 | 0.13 | 0.02 | 0.45 | 0.60 | 0.8 | 1.5 | 53.3 |
| Air content (%) | 200 | 0.08 | 0.12 | 0.46 | 0.67 | 0.8 | 4.6 | 17.4 |
| | | | | Cured Concrete | | | | |
| Cylinder strength (psi) | 400 | 264,694 | 0.0 | 254,848 | 519,543 | 721 | 3803 | 19.0 |

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