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16. Abstract

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The engineering properties of the dryer-drum mixtures generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures. Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced with dryer-drum plants.

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THE RESILIENT AND FATIGUE CHARACTERISTICS OF ASPHALT MIXTURES PROCESSED BY THE DRYER-DRUM MIXER

by

Manuel Rodriguez
Thomas W. Kennedy

Research Report Number 183-8

Tensile Characterization of Highway Pavement Materials

Research Project 3-9-72-183

conducted for

Texas
State Department of Highways and Public Transportation

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

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

December 1976

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 eighth in a series of reports summarizing the findings of a research project concerned with the tensile characterization of pavement materials for use in mixture and structural design. This report summarizes the findings of a limited study to evaluate the engineering properties of asphalt mixtures produced using a dryer-drum plant. This evaluation includes a comparison of the elastic and fatigue properties of the dryer-drum mixtures with the properties of asphalt mixtures produced with conventional plants. The effects of curing treatment and mixing temperature were evaluated; however, the effects of moisture could not be evaluated since no moisture differences were obtained. All specimens were plant mixed and laboratory compacted.

The engineering properties of the dryer-drum mixtures generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures. Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced with dryer-drum plants.

The study was financed by the State Department of Highways and Public Transportation as a part of the Cooperative Highway Research Program. Special appreciation is extended to Messrs. Avery Smith, Gerald Peck, and James L. Brown of the State Department of Highways and Public Transportation, who provided technical liason for the project, and to Messrs. James N. Anagnos and Pat S. Hardeman for their assistance with the testing program.

Manuel Rodriguez
Thomas W. Kennedy

December 1976

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.

Report No. 183-2, "Fatigue and Repeated-Load Elastic Characteristics of In-service Asphalt-Treated Materials," by Domingo Navarro and Thomas W. Kennedy, summarizes the results of a study on the fatigue response of highway pavement materials and the variation in fatigue life that might be expected in an actual roadway.

Report No. 183-3, "Cumulative Damage of Asphalt Materials Under Repeated-Load Indirect Tension," by Calvin E. Cowher and Thomas W. Kennedy, summarizes the results of a study on the applicability of a linear damage rule, Miner's Hypothesis, to fatigue data obtained utilizing the repeated-load indirect tensile test.

Report No. 183-4, "Comparison of Fatigue Test Methods for Asphalt Materials," by Byron W. Porter and Thomas W. Kennedy, summarizes the results of a study comparing fatigue results of the repeated-load indirect tensile test with the results from other commonly used tests and a study comparing creep and fatigue deformations.

Report No. 183-5, "Fatigue and Resilient Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test," by Adedare S. Adedimila and Thomas W. Kennedy, summarizes the results of a study on the fatigue behavior and the effects of repeated tensile stresses on the resilient characteristics of asphalt mixtures utilizing the repeated-load indirect tensile test.

Report No. 183-6, "Evaluation of the Resilient Elastic Characteristics of Asphalt Mixtures Using the Indirect Tensile Test," by Guillermo Gonzalez, Thomas W. Kennedy, and James N. Anagnos, summarizes the results of a study to evaluate possible test methods for obtaining elastic properties of pavement materials, to recommend a test method and preliminary procedure, and to evaluate properties in terms of mixture design.

Report No. 183-7, "Permanent Deformation Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test," by Joaquin Vallejo, Thomas W. Kennedy, and Ralph Haas, summarizes the results of a preliminary study which compared and evaluated permanent strain characteristics of asphalt mixtures using the repeated-load indirect tensile test.

Report No. 183-8, "The Resilient and Fatigue Characteristics of Asphalt Mixtures Processed by the Dryer-Drum Mixer," by Manuel Rodriguez and Thomas W. Kennedy, summarizes the results of a study to evaluate the engineering properties of asphalt mixtures produced using a dryer-drum plant.

ABSTRACT

This report summarizes the findings of a study to evaluate the engineering properties of asphalt mixtures produced using a dryer-drum plant. Included is a comparison of the elastic and fatigue properties of dryer-drum mixtures with the properties of asphalt mixtures produced with conventional plants. The effects of curing treatment and mixing temperature were evaluated; however, it was not possible to study the possible effects of moisture since no moisture differences were obtained. All specimens were plant mixed and laboratory compacted.

The engineering properties of the dryer-drum mixtures generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures. Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced with dryer-drum plants.

KEY WORDS: dryer-drum, blackbase, asphalt concrete, fatigue life, resilient modulus of elasticity, repeated-load indirect tensile test.

SUMMARY

This report summarizes the findings of a study to evaluate the engineering properties of asphalt mixtures produced using a dryer-drum plant and to compare these properties with the properties of asphalt mixtures produced using conventional plants. Plant-mixed and laboratory-compacted specimens were obtained from five dryer-drum projects. These specimens were tested at 24° C (75° F) using the repeated-load and static indirect tensile tests. Elastic strains, tensile strengths, and fatigue lives were estimated and compared to the characteristics obtained for the conventional mixtures. In addition, the effects of curing treatment and mixing temperature were evaluated; however, the effects of moisture could not be evaluated since no moisture differences were obtained.

The engineering properties of the dryer-drum mixtures generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures. Generally there were no differences between the elastic and fatigue properties of the cured and uncured specimens. The effects of mixing temperature were generally small. Based on this study and the experience and findings of others, it was concluded that satisfactory mixtures with moisture contents comparable to mixtures produced in conventional plants can be produced with dryer-drum plants.

IMPLEMENTATION STATEMENT

Based on the findings of this limited study and the experience and findings of others, it is recommended that the dryer-drum mixer be used to produce asphalt mixtures. The engineering properties of the dryer-drum mixtures were found to be equal to those of previously tested conventional mixtures. During future use, however, efforts should be made to answer questions concerning moisture and its effects. Thus an attempt should be made to determine how much moisture is present and the magnitude of its effects.

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CHAPTER 1. INTRODUCTION

In recent years the production of asphalt concrete mixtures has undergone an important change. A new process which simplifies both the overall procedure and the equipment used to produce asphalt concrete has been developed, the dryer-drum process. With this new method, a higher production rate at a lower price, with accompanying energy conservation, can be theoretically achieved.

Although several investigations have studied some of the properties of the asphalt concrete mixtures produced using a dryer-drum mixer, tensile strengths, resilient elastic properties, and fatigue properties for these kinds of mixtures are not readily available. Thus, the State Department of Highways and Public Transportation requested that a preliminary investigation be conducted to determine whether mixtures produced using a dryer-drum are satisfactory.

The purpose of the study summarized in this report was to evaluate the fatigue and elastic properties of asphalt mixtures produced using a dryer-drum plant. This evaluation basically involved a comparison of the properties of mixtures produced using a dryer-drum plant with the properties of asphalt-treated mixtures produced in conventional plants. In addition, the effect of mixing temperature was also evaluated.

The values of the fatigue and elastic characteristics reported in this study can be used in pavement design procedures which involve elastic layer systems and consider fatigue cracking.

Chapter 2 briefly summarizes the major results of previous investigations of the characteristics of asphalt-treated materials produced using a dryer-drum plant. Chapter 3 describes the experimental procedure used in this study. Chapter 4 discusses the analysis and findings of this study and Chapter 5 summarizes the conclusions and recommendations.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

The process of producing hot-mix emulsion mixtures in a revolving drum has been used for a number of years. However, more recently this process has been expanded to include preparation of mixtures using penetration grade asphalts. The first documented use of this process was in Asheville, North Carolina, in 1959 (Ref 4) and involved mixtures produced utilizing the dryer from a conventional plant. The project was discontinued due to lack of immediate acceptance. The more recent use of this process, using penetration grade asphalts, began about 1970, when plants in Iowa and Washington started operation (Ref 7).

The following summarizes the field experience with the dryer-drum during approximately the first four years of its use and is based on a report by Terrel and Miller (Ref 19).

EQUIPMENT AND OPERATIONS

The production and laydown of hot-mix asphalt materials is a system similar to that shown in Fig 1, which depicts a conventional plant (Ref 19). A principal goal of the drum mixer approach was to produce a high-quality mix and reduce the amount of equipment required. The dryer-drum process eliminates many pieces of equipment normally associated with a conventional plant, such as the hot elevator and tower, hot screens, hot lines and scales, and the pugmill mixer. Figure 1 with steps 4 through 8 eliminated represents the dryer-drum mixer.

The major components of a typical drum mixer plant are (Ref 18)

(1) three-bin feeder - aggregate gradation is controlled by a combination of variable-speed belts on each bin and variable gate opening;

(2) aggregate conveyor - the sorted aggregate flows up a weigh belt conveyor which can be interlocked to a variable capacity asphalt plant;

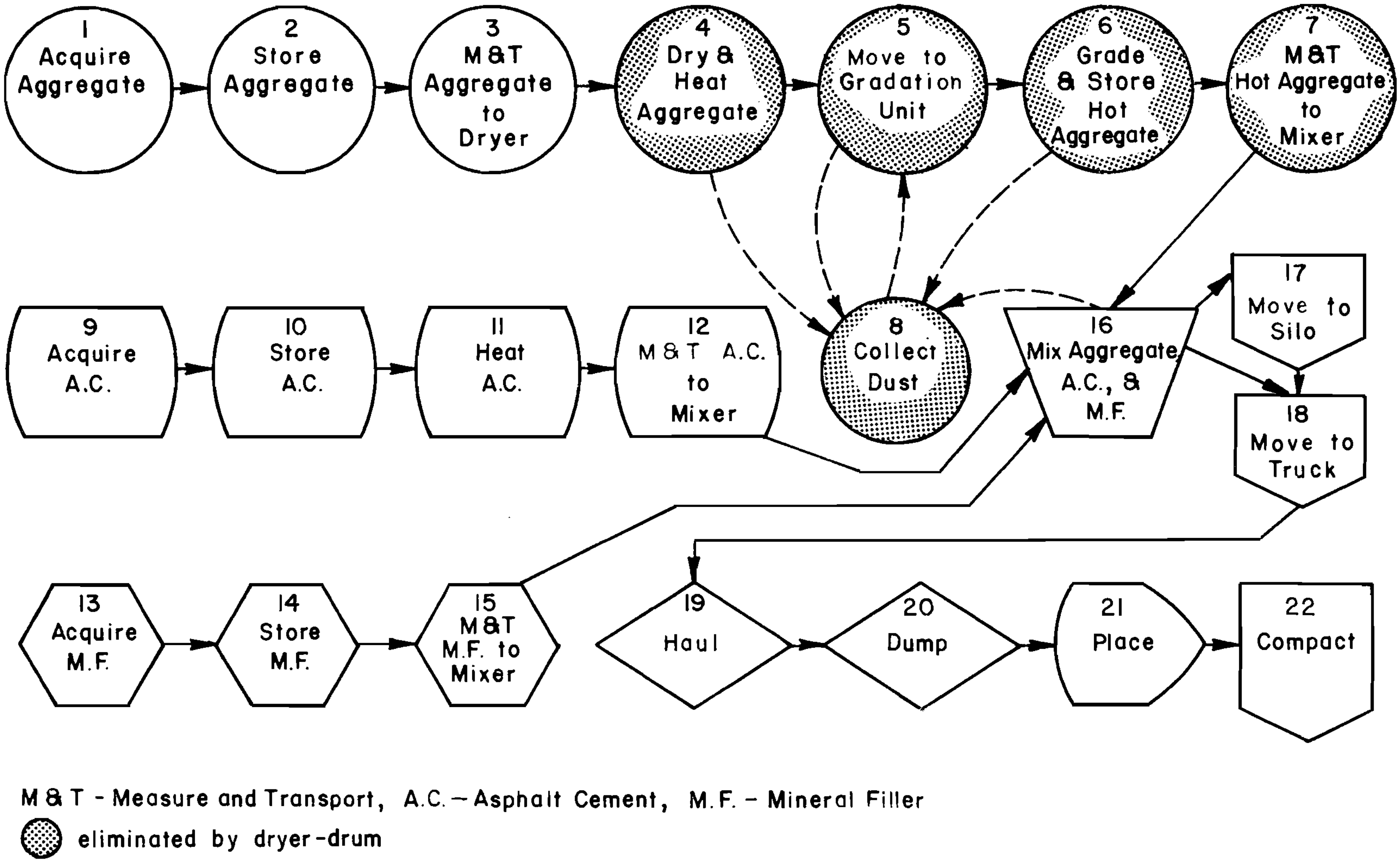


Fig 1. Conventional system for hot-mix asphalt production and paving (Ref 19).

(3) dryer-drum - the drum is fired by a conventional type burner and the flute design is such that the aggregate-asphalt blend is directed away from the hottest part of the flame;

(4) slat conveyor and surge silo - this type of temporary storage is convenient for most types of plants;

(5) control van - plant controls are operated from a central point.

The process of mixing the materials in the dryer-drum plant is as follows. The cold aggregates are blended on belts according to formula and fed into the dryer-drum, where pentration grade asphalt, with or without proprietory additives, is introduced. In the rotating drum, the aggregate is simultaneously heated, dried, and coated with asphalt. The mixture is discharged onto a conveyor and elevated to a storage silo and then transferred to the hauling equipment.

MIXTURE CHARACTERISTICS

The engineering characteristics for a number of mixtures processed by a dryer-drum plant have been evaluated. These characteristics include aging or hardening, effect of moisture, uniformity, compaction, and environmental effects.

Aging or Hardening

Hardening of the asphalt during the mixing process has always been a major concern. In a dryer-drum mixer, the asphalt is subject to very high temperatures and, in some cases, the flame itself, and thus, potential hardening was of primary concern.

The penetration data in Fig 2, for about 13.6×10^6 kg (15,000 tons) of mix produced in a pugmill in Washington, illustrate changes in the asphalt during the construction process (Refs 19 and 20). The dashed lines show that the penetration of an original 85/100 asphalt was reduced from about 93 to about 47 following the thin film oven test. The solid lines represent the penetration of asphalt recovered from mix samples at the plant and from the road several weeks after construction. The thin film oven test generally represents the aging of asphalt after about one year following mixing in a conventional pugmill type plant (Ref 19). As shown, the reduction in penetration is somewhat less for the drum mixer; therefore it would appear that hardening of the asphalt is not a severe problem for a dryer-drum plant and in many instances is less than for a conventional type plant.

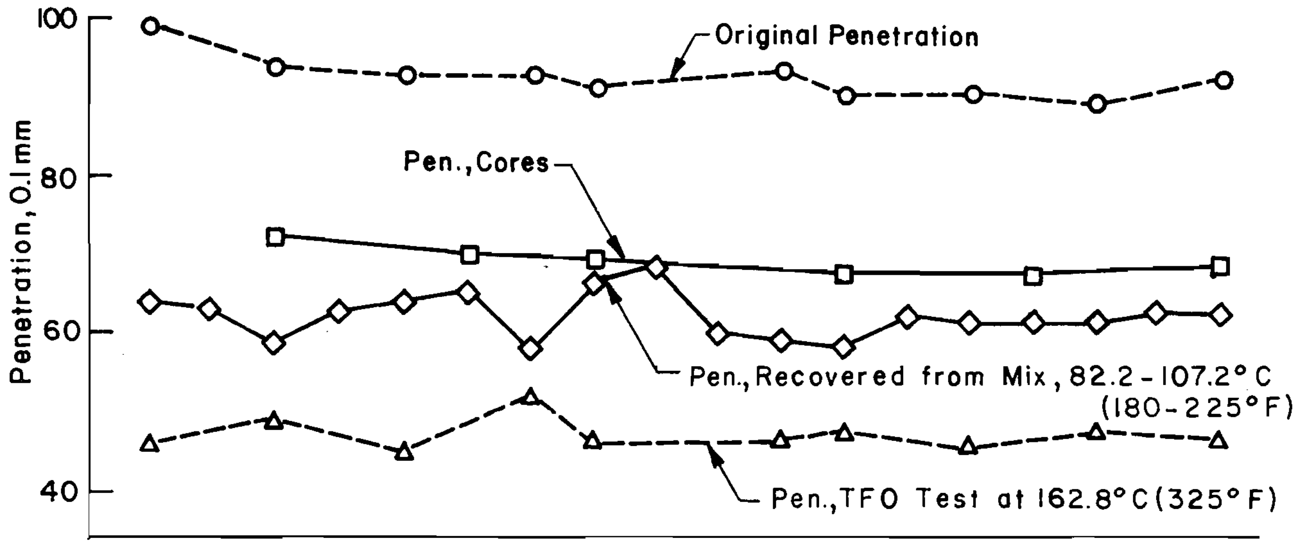


Fig 2. Hardening of 85/100 penetration asphalt for project in Washington (Ref 19).

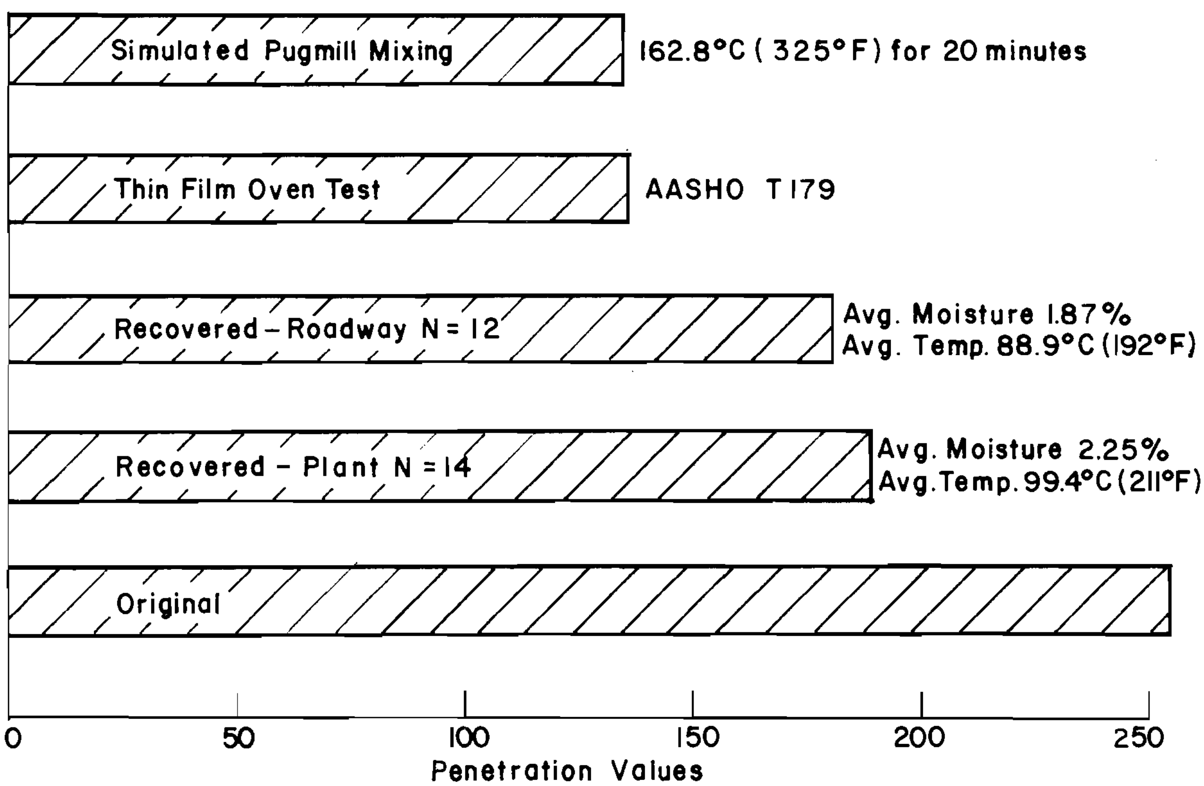


Fig 3. Hardening of 200/300 penetration asphalt for project in North Dakota (Refs 6 and 19).

From work reported by Granley (Ref 6), Terrel and Miller (Ref 19) indicated evidence of low rates of hardening. For example, Fig 3 indicates that the percent change of hardening for a 200/300 asphalt was similar to that for the harder asphalts. A survey of several states has shown that generally less hardening of the asphalt has been observed after mixing with a dryer-drum plant than with a conventional plant (Ref 10).

Asphalt pavements with a wide range of asphalts have been constructed. All paving grade asphalts, ranging from 60/70 penetration to 200/300 penetration, have been used. In addition, both MC-800 and emulsion mixes have been produced successfully.

Effect of Moisture

Paving operations for and laydown of mixtures produced by the drum mixer are virtually the same as they are for mixtures produced by a conventional plant; however, moisture is a key factor in the success of dryer-drum mixing. The characteristics of the mix at 100° C (212° F) with 2 percent water are similar to those of the conventional dry mix at 150° C (302° F) (Ref 19). Thus, production of workable mixes at lower temperatures is possible if moisture is present. Mixes have been made using this type of plant at temperatures of 65.6-71.1° C (150-160° F) with no serious problems; however, operation in this range may not be advisable because the moisture is insufficient and the temperature too low to provide the viscosity needed for handling (Ref 19).

A wide range of moisture variables was examined by the Chicago Testing Laboratory (Ref 2) using a batch type laboratory model of the drum dryer mixer. This study provided an opportunity to examine a typical batch of the mixture as it was heated. Figure 4 indicates that as the mixture was heated through temperatures of about 82 to 110° C (179.6 to 230.0° F), the water in the mixture was vaporized, which added to the mixing and coating action. In actual full-scale systems, this same action appeared to cause a fluffiness of the mix at about the discharge point, provided there was sufficient moisture available (Ref 19).

Another concern has been the long-term effect of moisture on the performance of asphalt mixtures. Traditionally, specifications generally have not permitted more than 0.5 percent water in the hot aggregate prior to mixing with asphalt in order to minimize stripping, loss of strength, and other water-related damages. As reported in Ref 19, data from a project in

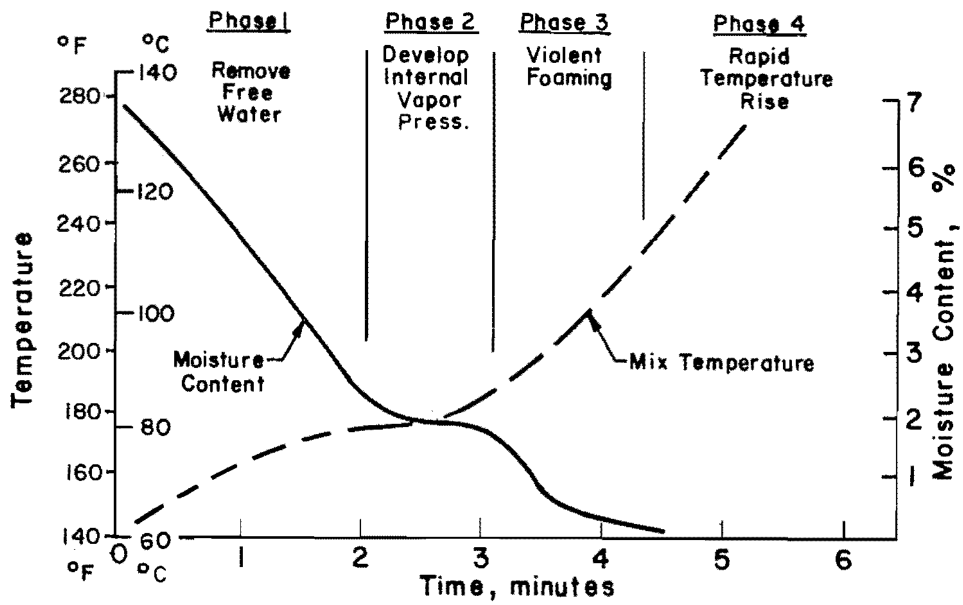


Fig 4. Relationship of moisture and temperature inside the drum (Ref 19).

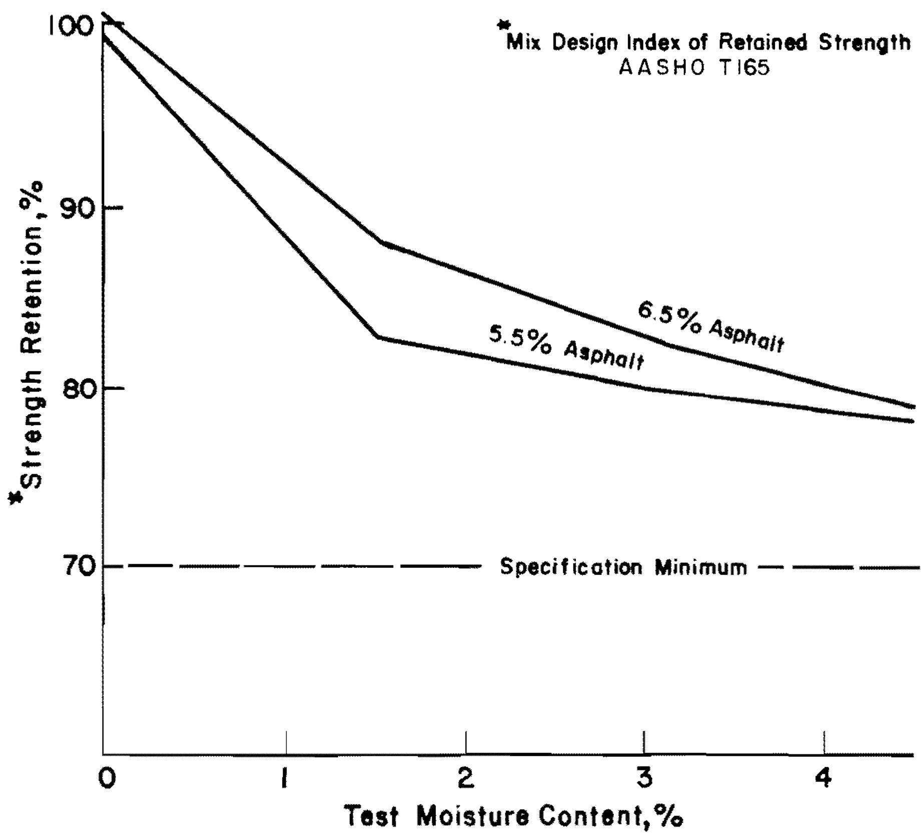


Fig 5. Strength retention after soaking (Ref 19).

Oregon (Ref 21) indicated that the loss of strength was not excessive and therefore the strength generally remained above acceptable minimums (Fig 5).

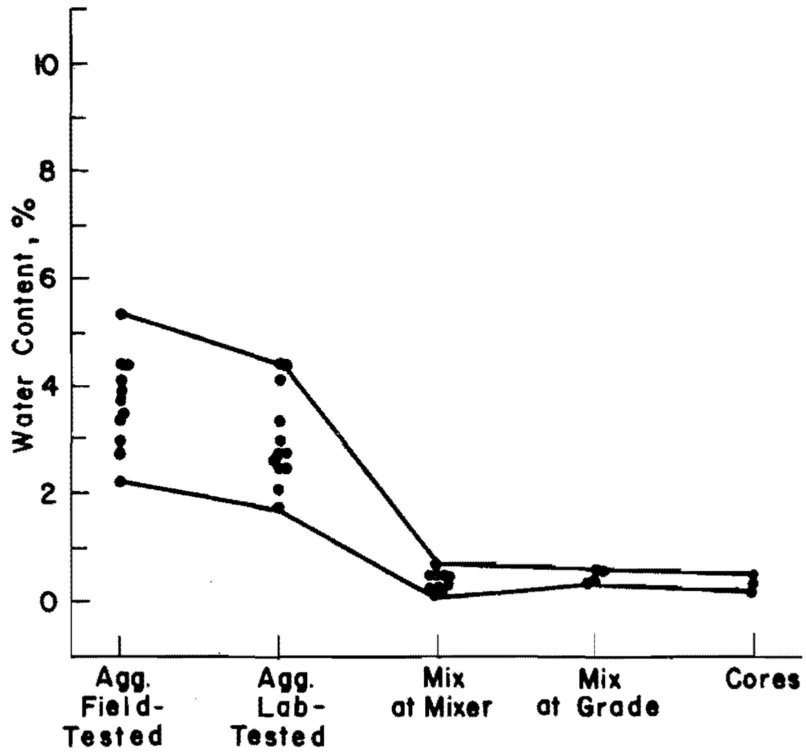
Most asphalt pavements in service, however, have a residual or equilibrium water content of about 1 percent or more, which is reached about one year after construction. Figure 6 shows the water content changes for two different material combinations (Ref 20). The aggregate stockpile in Fig 6a had an average water content of about 4 percent which eventually stabilized at about 0.5 percent. The aggregate material shown in Fig 6b was more porous and the stockpile was wetter. Therefore, the mixture tended to reach a higher equilibrium water content. Thus the drum mixer produced materials which tended to approach an equilibrium water content from the wet side, since the aggregates were not dried, rather than approaching it from the dry side as in conventionally produced mixtures.

Quality and Uniformity

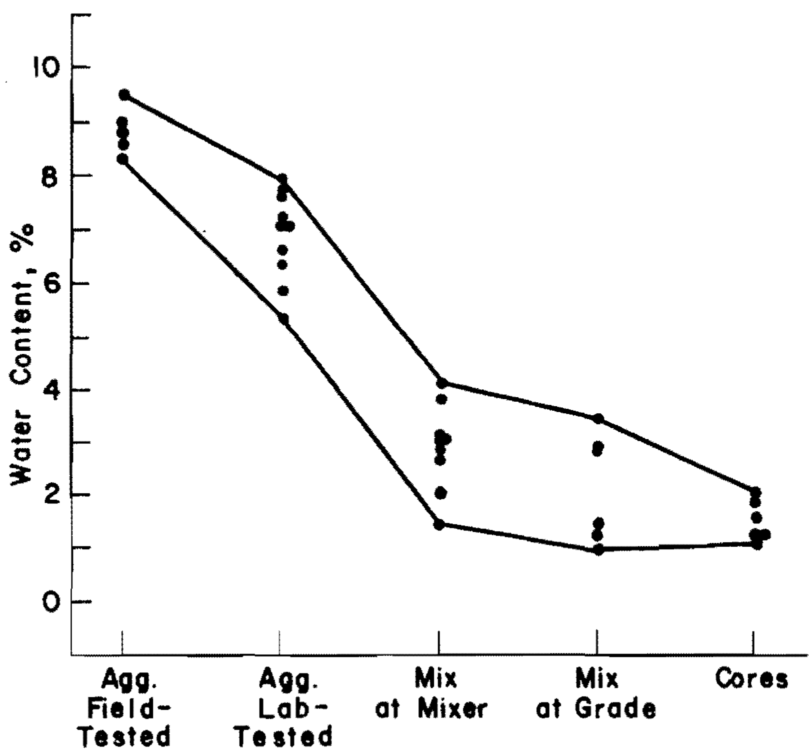
Results for a project at Port Ludlow show that strength and overall quality were approximately the same at the time of construction and 4-1/2 years later (Table 1). In addition, the overall serviceability of this pavement was excellent (Ref 19).

Uniformity of mixtures has also been found to be satisfactory. Granley (Ref 6) tested mixtures produced by several drum mixer plants and found that they compared well with those produced by conventional batch plants. Figure 7 includes data from three drum mixer plants and 26 batch plants. In Fig 7, the standard deviation of the asphalt content for the mixtures is shown and indicates that the uniformity of the drum dryer mixes is more than adequate. The variation in aggregate gradation for an Oregon project (Ref 21), which is typical for all projects tested to date, is shown in Fig 8 and indicates that the drum mixer plants do an excellent job of blending aggregates uniformly.

A survey of the use of dryer-drum plants in ten states showed that, although observations concerning the completed mixtures were generally favorable, some cautions were advised (Ref 10). The automatic burner controls cannot handle rapid changes in aggregate moisture and the asphalt contents from extractions did not always agree with the amounts specified.



(a) Dry aggregate.



(b) Wet, absorptive aggregate.

Fig 6. Water content of materials at various points in mixing process for a relatively dry and a wet aggregate (Ref 19).

TABLE 1. COMPARISON OF MIX PROPERTIES IN 1970 AND 1974, PORT LUDLOW, WASHINGTON (Ref 19)

Property		Drum Mixer Plant	
		July 1970	Dec 1974
Mix temperature of plant, °F		230	—
Water content, percent		0.39	0.44
Void content, percent		12.0	9.2
Aggregate stockpile water content		3.54	—
Aggregate gradation	3/4 in.	—	100
	1/2 in.	—	96.3
	1/4 in.	—	70.3
	No. 10	—	36.7
	No. 200	—	6.4
Marshall stability, lb		402	1026
Marshall flow, 0.01 in.		13	22
Unit weight, lb/cu ft		140.4	144.9

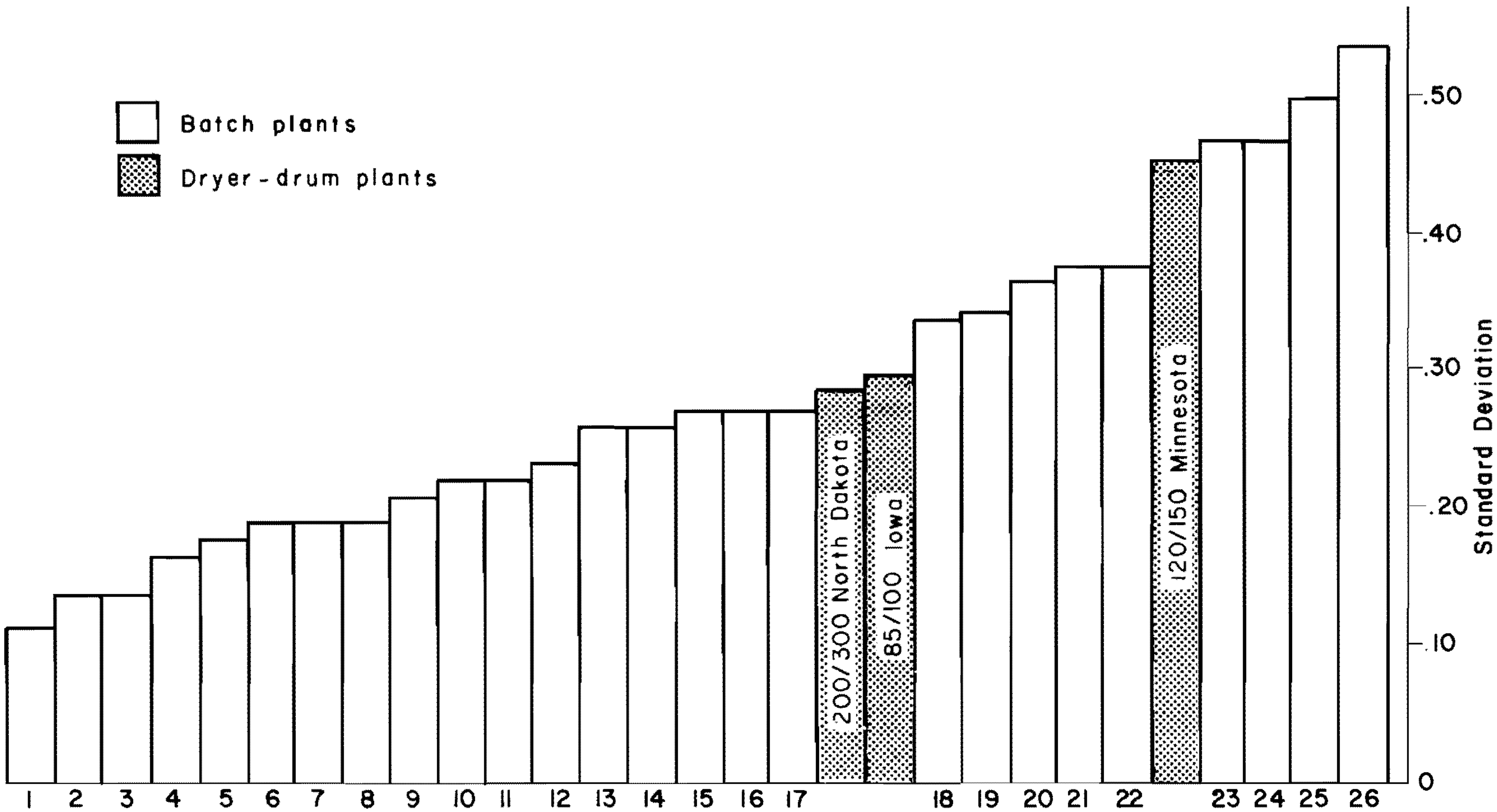


Fig 7. Uniformity of asphalt content (Refs 6 and 7).

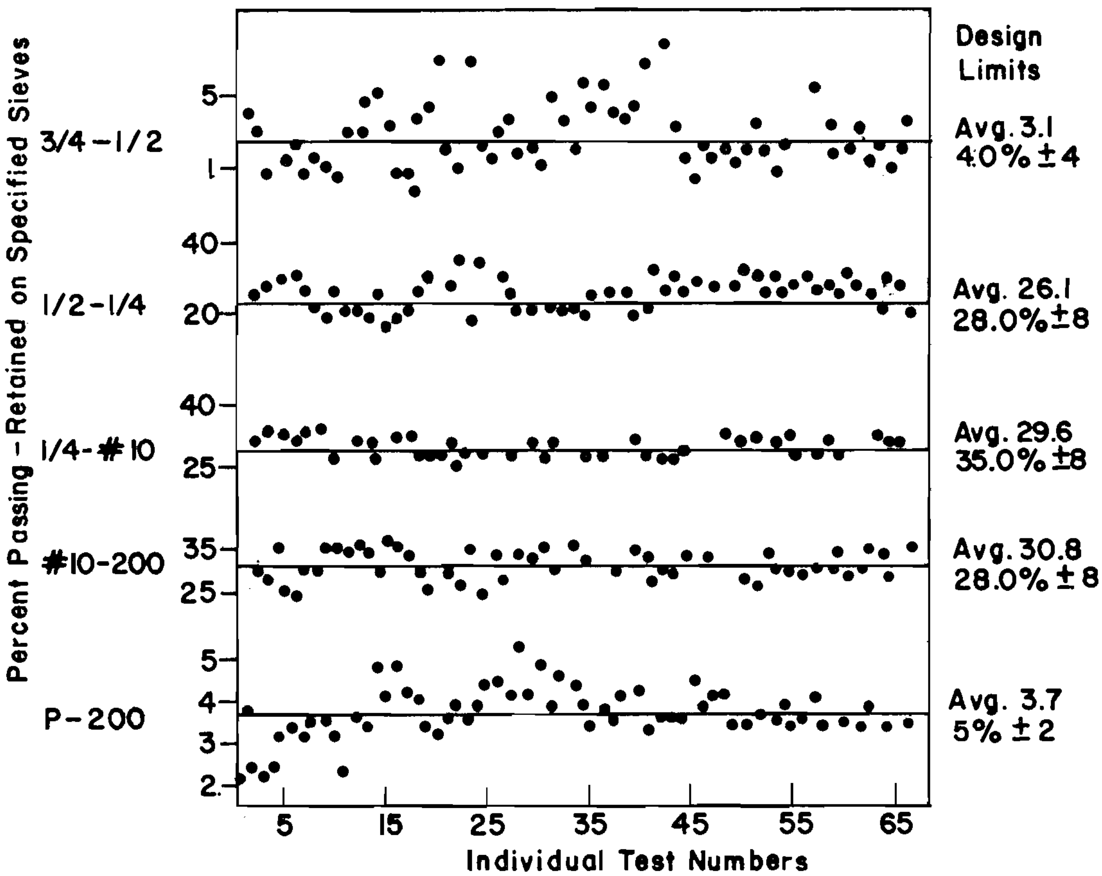


Fig 8. Uniformity of aggregate gradation (Ref 19).

Compaction

The compaction procedure is essentially the same as that used for conventionally produced paving mixtures. Figure 9 shows the results of tests in Washington (Ref 20). As the number of roller passes increased, pavement density increased. In addition, laydown temperature was 88° C (190° F) and gradually dropped from 88° C (190° F) to 68° C (154° F) at the end of testing. As shown by the asphalt plus water curve, water continued to evaporate and then appeared to stabilize. Thus it is possible to increase density at these lower temperatures.

Figure 10, which shows both percent compaction and air voids for the Oregon project, indicates that acceptable compacted mix can be produced.

Environmental Effects

During recent years, conventional batch plants have had to resort to expensive baghouse dust collection systems to meet rigid environmental protection standards. In the drum mixer the entire length of the drum acts as a dust filter, with the asphalt mixture readily removing the fines that would normally be blown out the stack. Many plants in the U. S. are operating legally under EPA limitations. Some of these plants have small cyclones, scrubbers, or other relatively simple devices, while others operate with no special dust collectors; however, a survey concerning the performance of the dryer-drum indicates that most plants need an additional recovery system to meet the air pollution requirements (Ref 10).

Energy

In general (Ref 19), the drum mixing plant conserves energy by

(1) reducing the amount of fuel oil required to fire the burner - less heat needs to be imparted to the asphalt concrete since less moisture must be removed from the mixture and the final mix temperature is typically lower than for conventionally produced mixes;

(2) reducing the amount of electrical energy required to power the plant; and

(3) reducing the amount of steel required in the hardware to achieve an equivalent rate of asphalt concrete production.

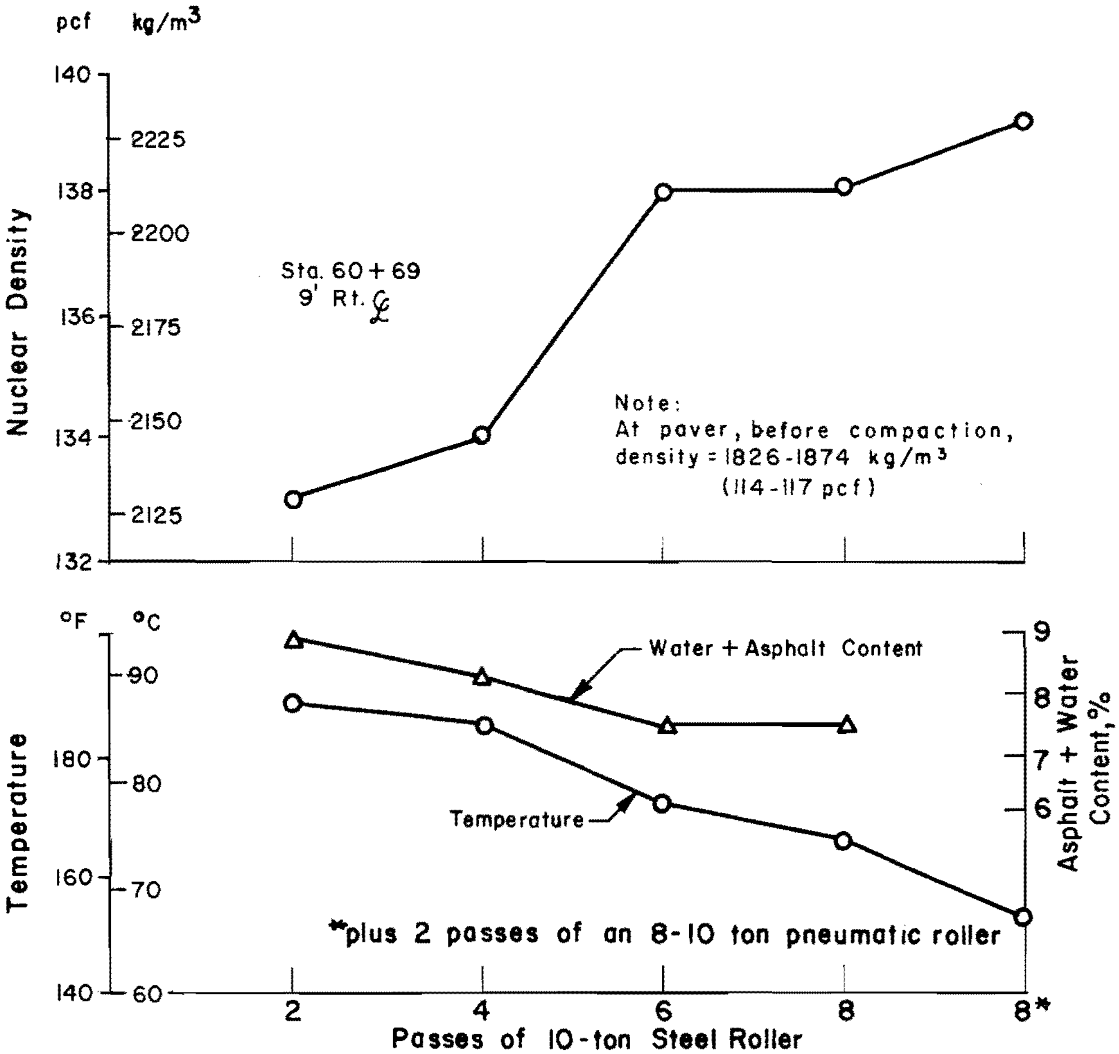


Fig 9. Effect of increased compactive effort during temperature drop and moisture evaporation (Ref 19).

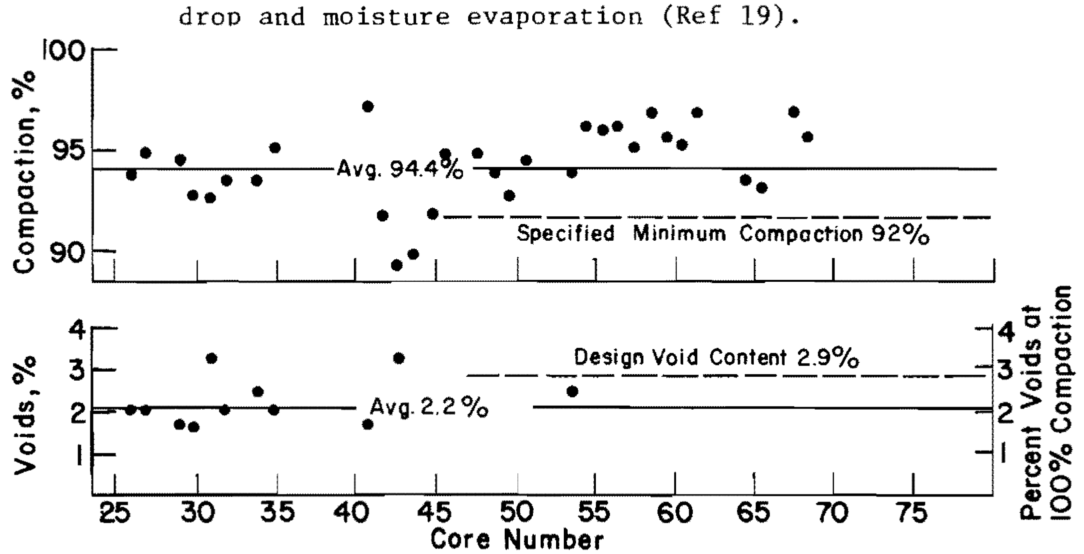


Fig 10. Uniformity of density and voids (Refs 19 and 21).

SUMMARY

Based on a review of the literature, it appears that a limited number of studies have been conducted to evaluate the dryer-drum process. In addition, there is no information available on the elastic and fatigue characteristics of asphalt-treated materials produced using a dryer-drum plant. Thus, there is a definite need for information concerning these characteristics so that an evaluation, based on these properties, can be made.

CHAPTER 3. EXPERIMENTAL PROGRAM

The objective of this study was to evaluate the fatigue and elastic properties of asphalt mixtures produced using a dryer-drum plant. To achieve this objective, specimens were prepared in the laboratory from mixtures obtained during construction of four highway projects in the State of Texas. Cores from pavements were not readily available at the time.

DESCRIPTION OF PROJECTS TESTED

Specimens of mixtures from five projects located in Districts 8, 11, 14, and 21 were tested. Summary information related to the projects is shown in Table 2. Figure 11 shows the geographical distribution of the districts from which the mixtures were obtained.

DESCRIPTION OF SPECIMENS

In order to study the effects of curing, which should be related to moisture, the specimens from the four projects in Districts 8, 11, and 21 were divided into two groups, cured and uncured. For the cured specimens, asphalt mixtures were obtained from the dryer-drum plants and dried to a constant weight at 121° C (250° F) and then compacted at the plant mixing temperature or at 121° C (250° F) as shown in Table 2. The uncured specimens were made by immediately compacting the asphalt mixtures obtained from the dryer-drum plants at the plant mixing temperature. All of the uncured specimens were coated with paraffin in order to retain any water that might be present in the mixture. The specimens from District 14 were used to evaluate the effect of the mixing temperature. These specimens involved mixtures produced at mixing temperatures of 96, 102, 107, and 121° C (205, 215, 225, and 250° F) and compacted at the same temperature immediately after mixing.

Prior to testing, all specimens were carefully measured and weighed. The specimens had nominal diameters of 102 mm (4 in.) and nominal heights of 51 mm (2 in.). After testing, a dry weight was obtained by allowing the

TABLE 2. DESCRIPTION OF ASPHALT CONCRETE PROJECTS

District Project	County	Treatment*	Mixing Temperature, °C (°F)	Compaction Temperature, °C (°F)	Number of Specimens: Fatigue	Number of Specimens: Static	Asphalt: Type	Asphalt: % Wt.**	Aggregate
8	Taylor	Cured	—	Same as mixing	9	3	AC-10	8.2	Lightweight
		Uncured	—		10	3			
11 (fine)	Shelby	Cured	—	121 (250)	10	3	AC-10	5.0	Crushed iron ore (fine gradation)
		Uncured	—	Same as mixing	12	3			
11 (coarse)		Cured	—	121 (250)	4	2	AC-10	5.0	Crushed iron ore (coarse gradation)
		Uncured	—	Same as mixing	4	2			
21	Hidalgo	Cured	124 - 129 (255 - 265)	121 (250)	13	2	AC-20	5.2	Limestone
		Uncured	124 - 129 (255 - 265)	124 - 129 (255 - 265)	12	2			
14	Hays	Uncured	96 (205)	96 (205)	7	2	AC-10	5.5	Limestone
		Uncured	107 (225)	107 (225)	7	2		5.3	
		Uncured	102 (215)	102 (215)	7	2		4.7	
		Uncured	121 (250)	121 (250)	7	2		4.9	

*Cured specimens were dried to a constant weight at 121° C (250° F) prior to compaction. Uncured specimens were compacted at the plant temperature immediately following mixing.

**% by weight of the total.

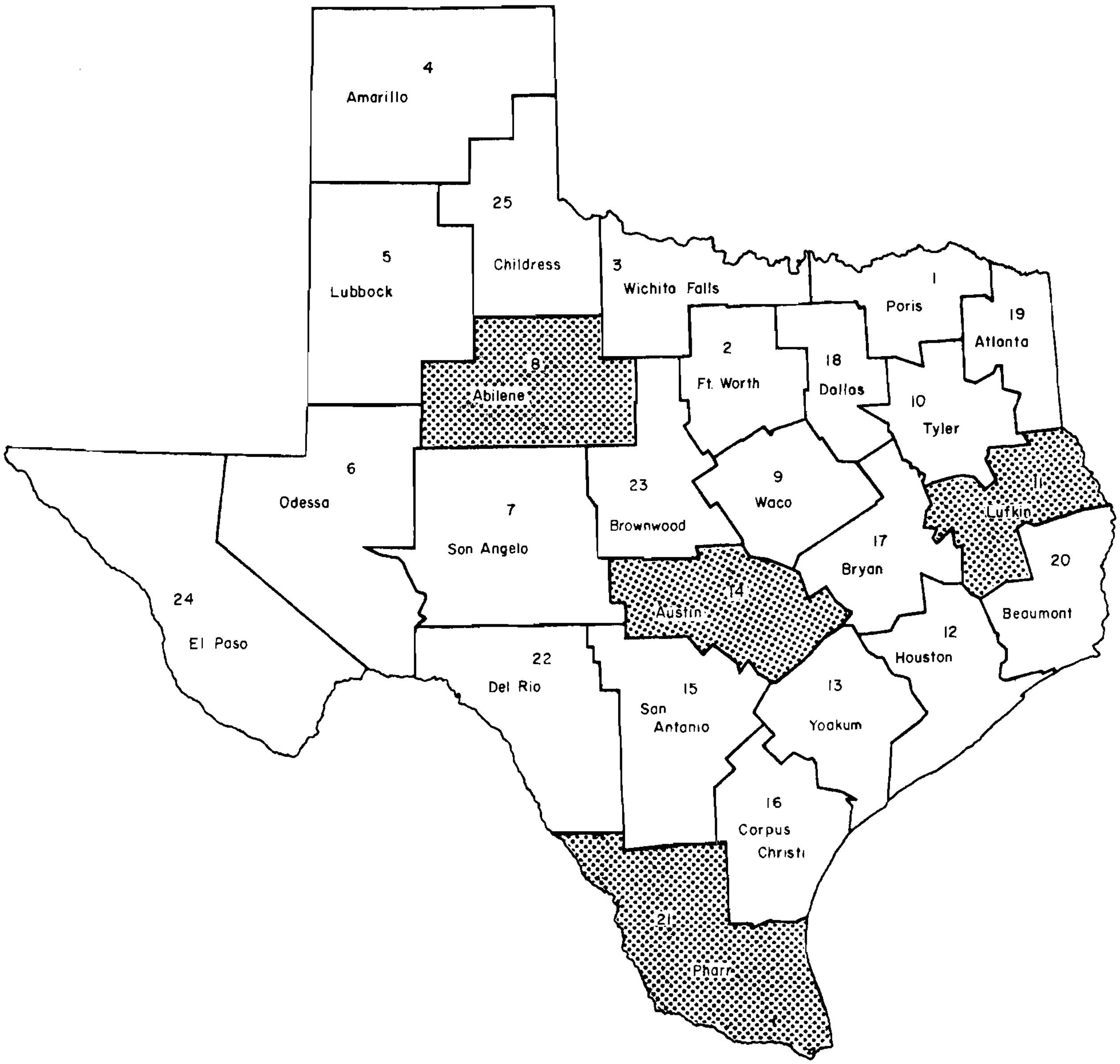


Fig 11. Districts from which specimens were obtained and tested.

specimen to dry at 121° C (250° F) until no additional weight loss occurred.

Since different factors from the five projects were studied and the number of specimens available for testing was limited, only two to three specimens were tested statically for each set of conditions. Similarly, for the fatigue and resilient properties, two to three specimens were tested at each stress level for each set of conditions. Previous studies (Refs 1 and 15) reported that the relationship between fatigue life and tensile stress is a linear relationship; thus, only two stress levels were used in this study for each condition.

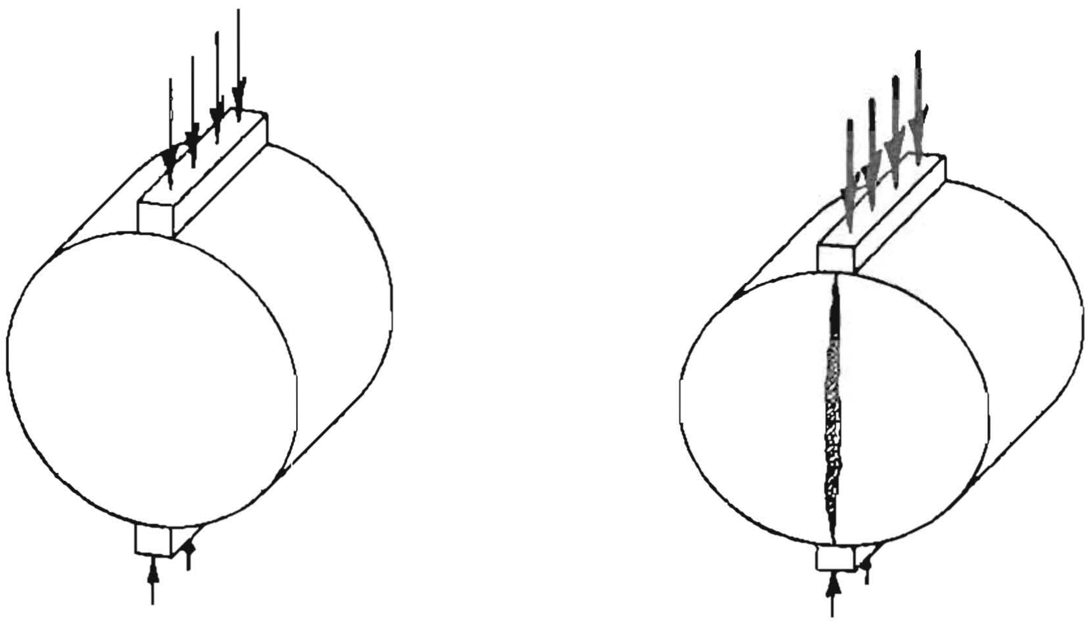
DESCRIPTION OF THE INDIRECT TENSILE TEST

All specimens were tested using the indirect tensile test, which involves loading a cylindrical specimen with either static or repeated compressive loads acting parallel to and along the vertical diametral plane, as shown in Fig 12a. The compressive load is distributed through 13-mm (0.5-in.)-wide steel loading strips which are curved at the interface to fit the specimen. This method of loading produces a fairly uniform tensile stress perpendicular to the plane of the applied load and along the vertical diametral plane which ultimately causes the specimen to fail by splitting along the vertical diameter (Fig 12b). Estimates of the tensile strength, modulus of elasticity, and Poisson's ratio can be computed when the applied load and corresponding vertical and horizontal deformations are known.

Test Equipment

The test equipment was basically the same as that used in previous studies at the Center for Highway Research and included a loading frame, a loading head, and an MTS closed-loop electrohydraulic system to apply load and to control deformation rate (Fig 13). The loading head was a modified commercially available die set, with the lower and upper platens constrained so that the platens remain parallel.

The deformations were measured by DC linear variable differential transducers (LVDT's). In order to obtain the individual vertical deformations, an LVDT was positioned above the upper platen (Fig 14). A horizontal deformation transducer consisting of two LVDT's was used to monitor the horizontal deformation of the specimen for selected load applications. A



(a) Compressive load being applied. (b) Specimen failing in tension.

Fig 12. Indirect tensile test loading and failure.

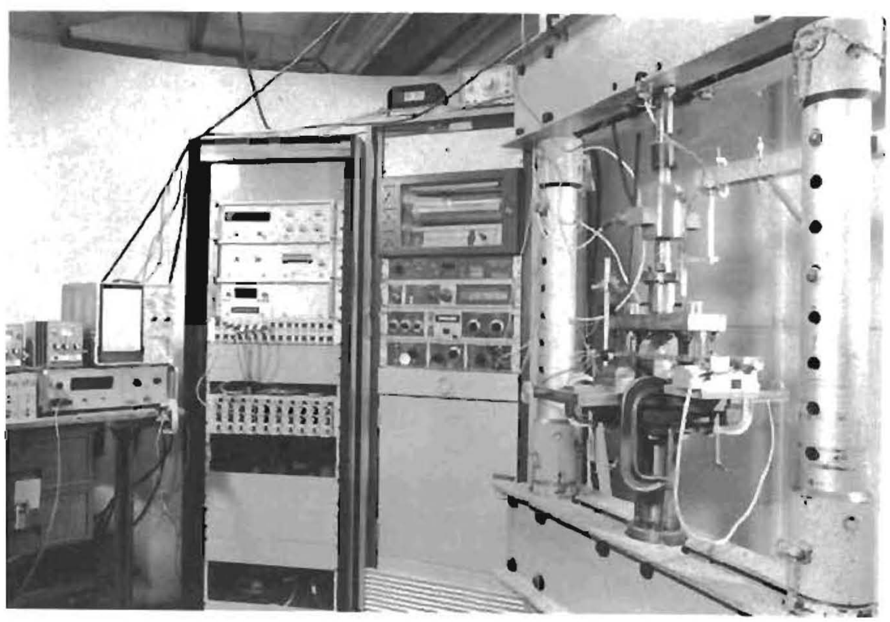


Fig 13. Basic testing equipment.

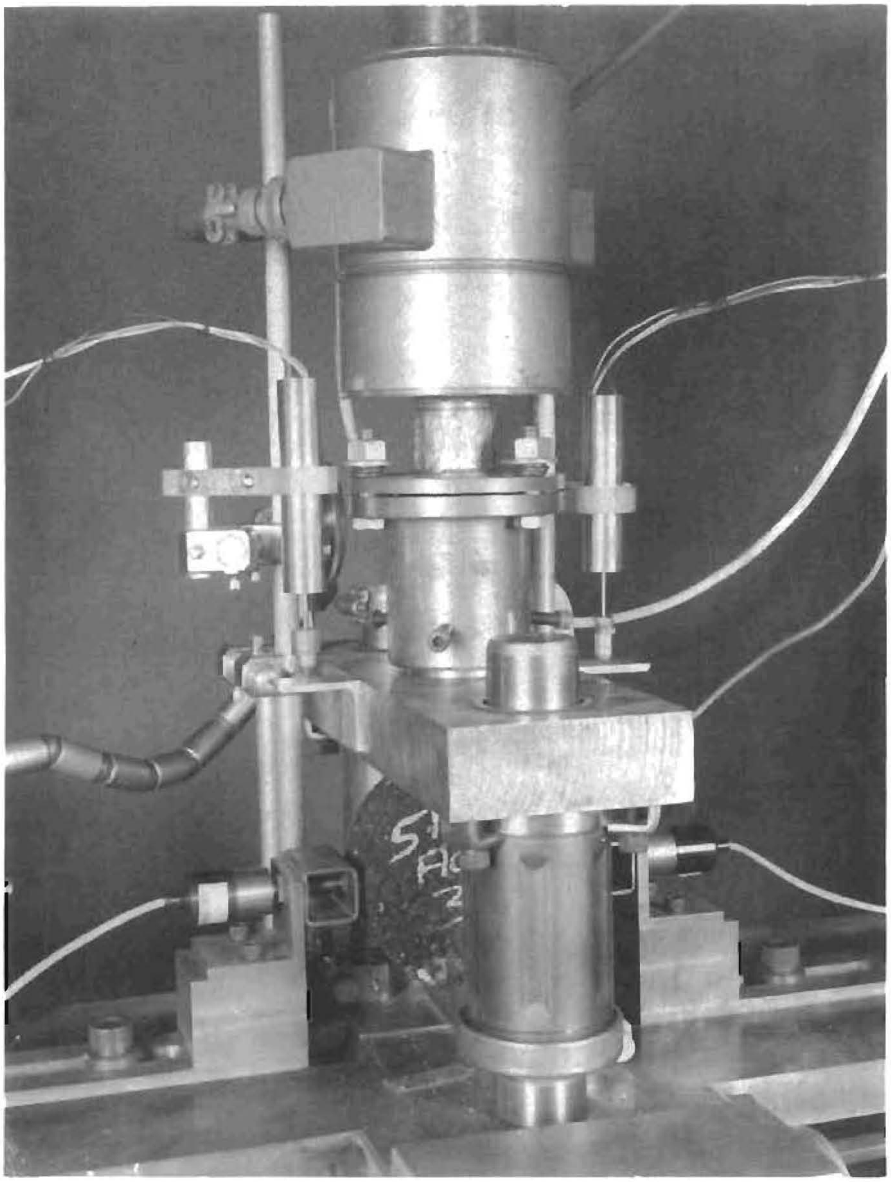


Fig 14. Repeated-load indirect tensile test.

typical horizontal and vertical deformation versus time pattern is illustrated in Fig 15, along with the corresponding load-time pulse.

The individual vertical and horizontal deformations were recorded on a pair of X-Y plotters, Hewlett-Packard model 7001-A.

Static Test Procedure

In order to prevent impact loading and to minimize the effect of seating the loading strip, a preload of 89 N (20 lb) was applied to the specimen. Then, the specimen was loaded at a rate of 51 mm (2 in.) per minute. The loads and deformations were monitored by two X-Y plotters, one recording load and horizontal deformation and the other recording load and vertical deformation.

From these recordings, corresponding loads, vertical deformations, and horizontal deformations were obtained and, along with the dimensions for each specimen, were used as input for the computer program MODLAS 9 to calculate the tensile strength and static elastic properties of the materials tested.

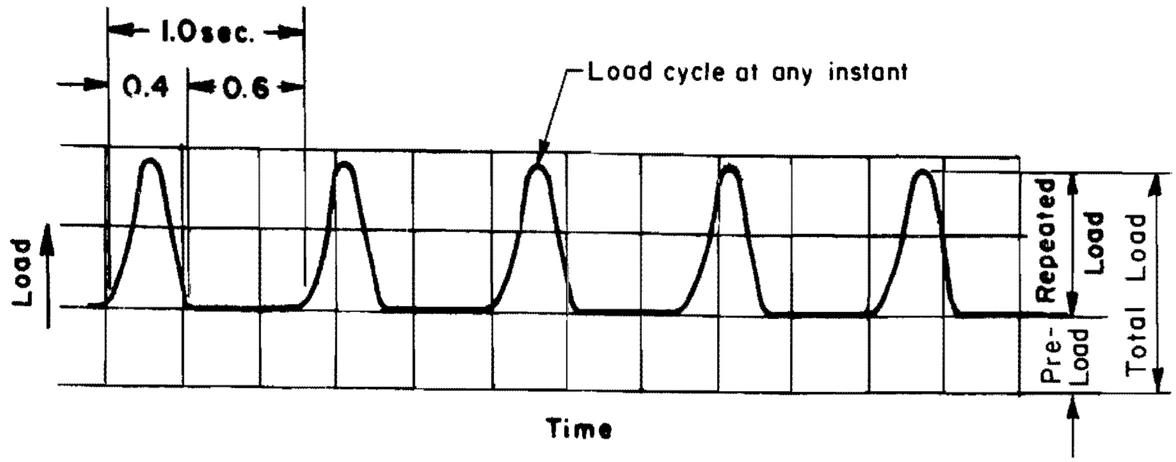
Repeated Load-Test Procedure

A seating load of 89 N (20 lb), which corresponds to a stress of about 1.1 N/cm^2 (1.5 psi), was applied in these tests also. Then, repeated loads producing maximum stresses ranging from 3 N/cm^2 (4.4 psi) to 22.1 N/cm^2 (32 psi) were applied at a frequency of one cycle per second, 1 Hz, with a 0.4-second load duration and a 0.6-second rest period. All tests were conducted at 24° C (75° F) and were continued until failure occurred, which was considered to be when the specimen fractured completely. Therefore, fatigue life N_f was the number of cycles corresponding to this failure.

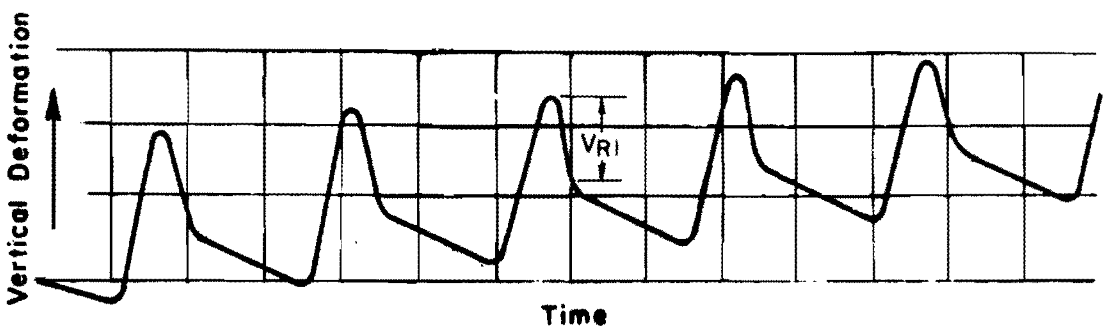
The individual horizontal and vertical deformations were recorded for the 25th and 50th cycles and for cycles corresponding to approximately 30, 50, and 70 percent of the fatigue life.

METHODS OF ANALYSIS

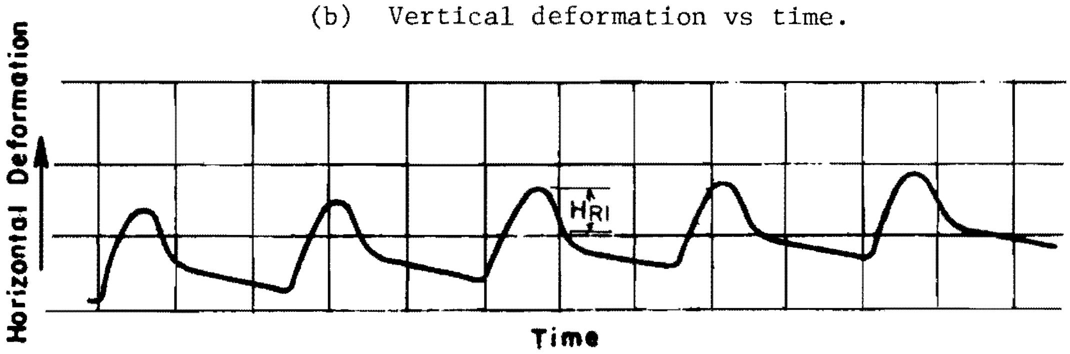
The parameters analyzed in this study for the static test were tensile strength, modulus of elasticity, and Poisson's ratio, and, for the repeated test, they were fatigue life, instantaneous resilient modulus of elasticity, and instantaneous resilient Poisson's ratio.



(a) Load-time pulse.



(b) Vertical deformation vs time.



(c) Horizontal deformation vs time.

Fig 15. Typical load and deformation versus time relationships for repeated-load indirect tensile test.

In order to calculate the static tensile and elastic properties, corresponding loads, vertical deformations, and horizontal deformations were obtained from the recordings and, along with the dimensions, were used as input for the computer program MODLAS 9.

The instantaneous resilient properties were evaluated at the 25th and 50th cycles and at cycles corresponding to approximately 30, 50, and 70 percent of fatigue life. Instantaneous resilient deformations V_{RI} and H_{RI}, as shown in Fig 15, and the repeated load were used as input in the computer program MODLAS 10M to calculate the resilient elastic properties.

CHAPTER 4. ANALYSIS AND EVALUATION

The objective of this study was to evaluate the fatigue and elastic properties of asphalt mixtures produced using a dryer-drum plant. This evaluation involved a comparison of these properties with the properties of asphalt mixtures produced by a conventional plant. It had been hoped that the effects of moisture could be evaluated; however, mixtures with high moisture contents were not available. Factors which could be evaluated were curing treatment and mixing temperature.

The effect of water content could not be evaluated since no appreciable difference in water content was observed between the cured and uncured specimens of any given mixture (Table 3). In fact, the water contents were approximately equal to those which might be expected in conventional plants. It should be noted, however, that, even if there had been a moisture difference, it would be difficult to isolate its effect since the curing treatments also differed. Future studies should consider this fact.

FATIGUE PROPERTIES

Fatigue life was defined as the number of load applications required to completely fracture the specimen. The fatigue lives and characteristics for the five projects are summarized in Table 3.

Fatigue Life - Stress Relationships

Based on the results of previous studies (Refs 1 and 15) which showed that a linear relationship exists between the logarithm of applied stress and the logarithm of fatigue life, only two stress levels were used in this study.

This linear relationship between fatigue life and stress (Fig 16) can be expressed either in the form

$$N_f = K_2 \left(\frac{1}{\sigma_T} \right)^{n_2} \qquad (4.1)$$

TABLE 3. SUMMARY OF FATIGUE RESULTS

District Project	Aggregate	Asphalt Content, %	Treatment*	Mixing Temperature, °C (°F)	Compaction Temperature, °C (°F)	Mean Water Content, %	Stress Level, N/cm^2	Number of Specimens	Fatigue Life: Mean	Fatigue Life: Coefficient of Variation, %	Fatigue Constants**: K_2	Fatigue Constants**: K_2'	Fatigue Constants**: n_2	R^2
8	Lightweight	8.2	Cured	—	Same as mixing	0.2	6.0	4	9,165	40	4.99×10^5	1.17×10^7	2.28	0.75
							3.0	5	46,260	60				
			Uncured	—		1.7	6.0	5	10,484	19	2.30×10^5	2.53×10^6	1.73	0.90
							3.0	5	35,195	25				
11 (fine)	Crushed iron ore (fine gradation)	5.4	Cured	—	121 (250)	1.2	6.0	4	6,019	31	1.83×10^5	2.66×10^6	1.93	0.87
							3.0	6	22,270	19				
			Uncured	—	Same as mixing	1.7	6.0	6	8,237	41	2.15×10^5	2.82×10^6	1.86	0.86
							3.0	6	28,245	14				
11 (coarse)	Crushed iron ore (coarse gradation)	5.0	Cured	—	121 (250)	1.1	6.0	2	3,700	34	3.32×10^4	1.86×10^5	1.24	0.86
							3.0	2	8,500	2				
			Uncured	—	Same as mixing	1.3	6.0	2	4,319	47	4.72×10^4	3.14×10^5	1.36	0.77
							3.0	2	10,562	15				
21	Limestone	5.2	Cured	124 - 129 (255 - 265)	121 (250)	0.3	22.1	6	12,100	68	1.08×10^7	2.52×10^8	2.28	0.77
							5.5	7	314,044	74				
			Uncured	124 - 129 (255 - 265)	124 - 129 (255 - 265)	0.3	22.1	6	2,594	53	1.20×10^5	7.05×10^5	1.28	0.74
							5.5	6	16,340	77				
14	Limestone	5.5	Uncured	96 (205)	96 (205)	—	6.0	2	32,267	19	2.44×10^6	8.97×10^7	2.60	0.81
							3.0	2	139,912	12				
		5.3		107 (225)	107 (225)	—	6.0	2	27,930	27	2.77×10^6	1.09×10^8	2.65	0.95
							3.0	3	150,702	19				
		4.7		102 (215)	102 (215)	—	6.0	1	37,841	—	6.71×10^5	1.34×10^7	2.16	—
							3.0	3	70,586	63				
		4.9		121 (250)	121 (250)	—	6.0	4	35,128	20	5.53×10^5	4.68×10^6	1.54	0.87
							3.0	3	104,118	31				

*Cured specimens were dried to a constant weight at 121° C (250° F) prior to compaction. Uncured specimens were compacted at the plant temperature immediately following mixing.

**$\log N_f = \log K_2 - n_2 \log \sigma_T = \log K_2' - n_2 \log \Delta\sigma$

$1\ N/cm^2 = 1.4504$ psi

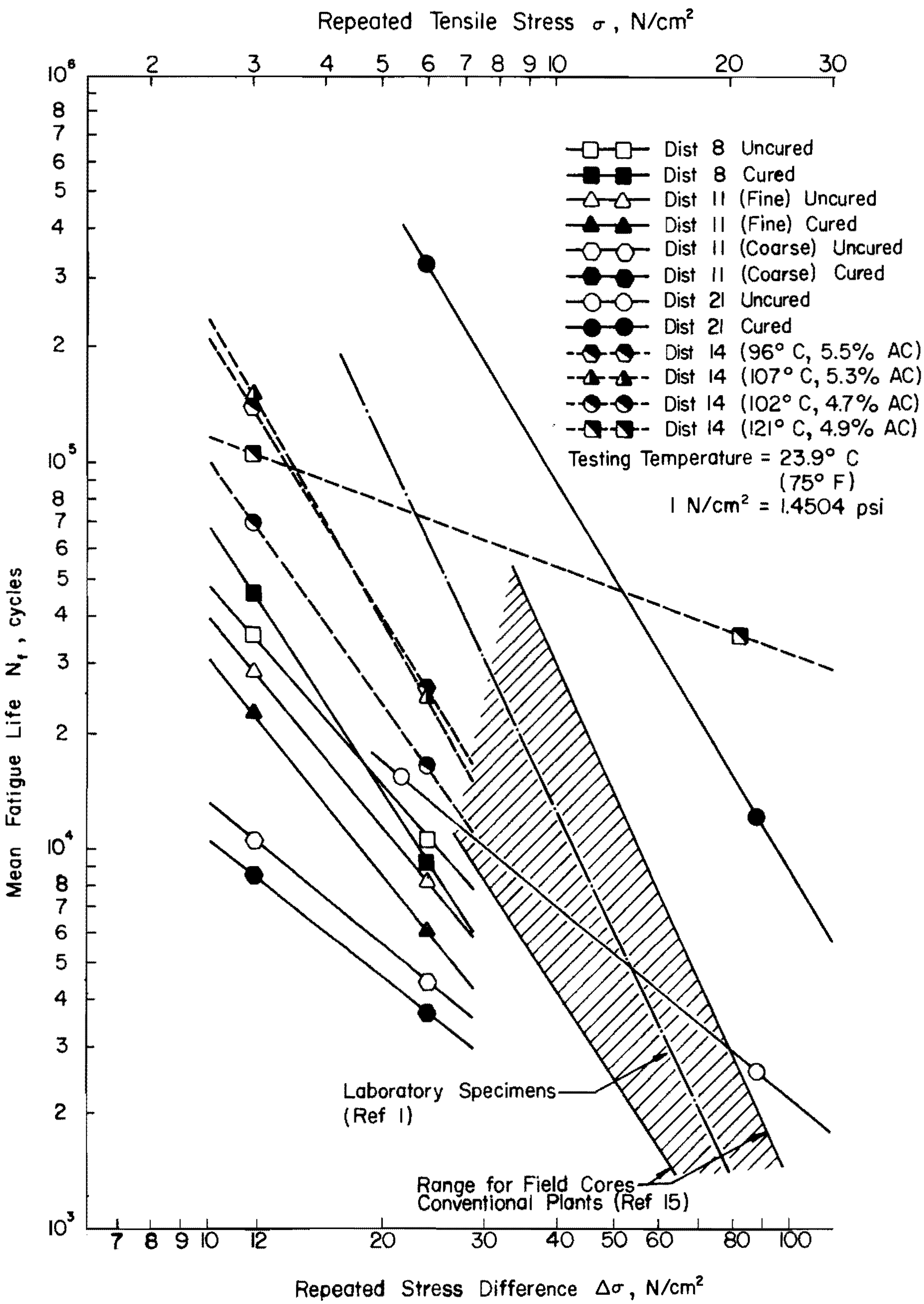


Fig 16. Logarithmic relationships between fatigue life and stress.

or in the form

$$N_f = K_2'\left(\frac{1}{\Delta\sigma}\right)^{n_2} \tag{4.2}$$

where

N_f = fatigue life, cycles,

σ_T = applied tensile stress, N/cm^2,

$\Delta\sigma$ = stress difference $\simeq 4\sigma_T$, N/cm^2,

K_2 = material constant, the antilog of the intercept value of the logarithmic relationship between fatigue life and tensile stress,

K_2' = material constant, the antilog of the intercept value of the logarithmic relationship between fatigue life and stress difference, and

n_2 = material constant, the absolute value of the slope of the logarithmic relationship between fatigue life and tensile stress or stress difference.

Previous studies (Refs 1 and 16) have shown the latter form, Eq 4.2, to be more realistic and compatible with other test methods. For the indirect tensile test, the stress difference is approximately equal to $4\sigma_T$ near the center of the specimen.

Comparison with Conventional Mixtures

Values of the constants n_2 , K_2 , and K_2' together with correlation coefficients R^2 were obtained by linear regression and are summarized in Table 3.

Values of n_2 were fairly constant, ranging from 1.24 to 2.28. More important, however, is the fact that these values are low compared to previously reported values for field cores of mixtures produced using a conventional plant. Monismith (Ref 13) reported values ranging from 1.85 to 6.06 and Navarro and Kennedy (Ref 15) reported values ranging from 1.58 to 5.08. Since $\frac{1}{\sigma}$ is always less than 1.0, lower values of n_2 generally would indicate higher values of fatigue life, but the higher values would tend to occur at higher stress levels.

Values of K_2' ranged from 7.05×10^5 to 2.52×10^8. These values are small compared to previously reported values of K_2' for mixtures produced using conventional plants, which should indicate lower fatigue lives. Navarro and Kennedy (Ref 15) reported values of K_2' ranging from 1.38×10^6 to 1.24×10^{15}. Monismith (Ref 14) reported values in the range of 4.02×10^7 to 4.31×10^{17}. Adedimila and Kennedy (Ref 1), for laboratory specimens at the optimum asphalt content, reported values of K_2' of 3.68×10^9 for gravel mixtures and 1.44×10^9 for limestone mixtures.

The logarithmic relationships shown in Fig 16 generally indicate that the dryer-drum mixtures had lower fatigue lives for the range of stress shown. As indicated by the n values, however, the reverse would probably occur at very high stress levels.

Variation of Fatigue Life

The coefficients of determination R^2 for the various logarithmic relationships are shown in Table 3. These values ranged from 0.73 to 0.90, indicating an adequate correlation.

The coefficients of variation of fatigue life (Table 3) ranged from 2 to 82 percent; these values are generally lower than those reported by Navarro and Kennedy (Ref 15). This is probably partially due to the fact that the specimens were laboratory compacted. In some projects, the coefficients of variation decreased with an increase in applied tensile stress; in other projects, the reverse was true. Similar results were reported by Navarro and Kennedy (Ref 15).

STRENGTH AND ELASTIC PROPERTIES

The elastic characteristics were obtained with the use of static and repeated-load tests. From the static test, estimates of tensile strength, modulus of elasticity, and Poisson's ratio were determined. From the repeated-load test, fatigue life, instantaneous resilient modulus of elasticity, and instantaneous resilient Poisson's ratio were estimated. Tables 4 and 5 summarize the static and repeated-load test results and include the means and the coefficients of variation.

TABLE 4. SUMMARY OF TENSILE STRENGTHS AND STATIC ELASTIC PROPERTIES

District Project	Aggregate	Asphalt Content, %	Treatment*	Mixing Temperature, °C (°F)	Compaction Temperature, °C (°F)	Mean Water Content, %	Number of Specimens	Tensile Strength Mean, N/cm^2	Tensile Strength Coefficient of Variation, %	Modulus of Elasticity Mean, 10^3 N/cm^2	Modulus of Elasticity Coefficient of Variation, %	Poisson's Ratio Mean	Poisson's Ratio Coefficient of Variation, %
8	Lightweight	8.2	Cured	—	Same as mixing	0.2	3	42	18	56	21	0.14	52
			Uncured	—		1.7	3	44	11	61	11	0.24	11
11 (fine)	Crushed iron ore (fine gradation)	5.4	Cured	—	121 (250)	1.2	3	70	9	79	10	0.37	26
			Uncured	—	Same as mixing	1.7	3	71	5	72	3	0.26	17
11 (coarse)	Crushed iron ore (coarse gradation)	5.0	Cured	—	121 (250)	1.1	2	69	25	60	1	0.42	27
			Uncured	—	Same as mixing	1.3	2	73	24	71	33	0.37	14
21	Limestone	5.2	Cured	124 - 129 (255 - 265)	121 (250)	0.3	2	102	4	183	29	0.25	65
			Uncured	124 - 129 (255 - 265)	124 - 129 (255 - 265)	0.3	2	85	42	164	33	0.22	30
14	Limestone	5.5	Uncured	96 (205)	96 (205)	—	2	85	20	108	12	0.15	80
		5.3		107 (225)	107 (225)	—	2	68	2	88	7	0.19	44
		4.7		102 (215)	102 (215)	—	2	85	17	98	8	0.16	48
		4.9		121 (250)	121 (250)	—	2	70	6	104	15	0.17	7

*Cured specimens were dried to a constant weight at 121° C (250° F) prior to compaction. Uncured specimens were compacted at the plant temperature immediately following mixing.

1 N/cm^2 = 1.4504 psi

TABLE 5. SUMMARY OF REPEATED-LOAD ELASTIC PROPERTIES

District Project	Aggregate	Asphalt Content, %	Treatment*	Mixing Temperature, °C (°F)	Compaction Temperature, °C (°F)	Mean Water Content, %	Applied Tensile Stress, N/cm²	Number** of Specimens	Instantaneous Resilient Modulus		Instantaneous Resilient Poisson's Ratio	
									Mean, 10^3 N/cm²	Coefficient of Varia-tion, %	Mean	Coefficient of Varia-tion, %
8	Lightweight	8.2	Cured	—	Same as mixing	0.2	6.0	4 (3)	141	25	—	—
							3.0	5 (2)	128	25	0.17	—
			Uncured	—		1.7	6.0	5	168	11	0.12	43
							3.0	5	143	13	0.13	35
11 (fine)	Crushed iron ore (fine gradation)	5.4	Cured	—	121 (250)	1.2	6.0	4	173	6	0.18	19
							3.0	6	189	16	0.13	39
			Uncured	—	Same as mixing	1.7	6.0	6	184	9	0.17	53
							3.0	6	190	14	0.13	46
11 (coarse)	Crushed iron ore (coarse gradation)	5.0	Cured	—	121 (250)	1.1	6.0	2	168	7	0.22	19
							3.0	2	151	4	0.21	47
			Uncured	—	Same as mixing	1.3	6.0	2 (1)	184	15	0.38	—
							3.0	2	155	14	0.11	7
21	Limestone	5.2	Cured	121 (250)	121 (250)	0.3	22.1	6	332	13	0.16	—
							5.5	7 (5)	266	15	0.07	—
			Uncured	124 - 129 (255 - 265)	124 - 129 (255 - 265)	0.3	22.1	6 (4)	349	6	0.12	53
							5.5	6 (5)	225	12	0.07	74
14	Limestone	5.5	Uncured	96 (205)	96 (205)	—	6.0	2	276	24	0.27	16
							3.0	2	213	11	0.17	9
		5.3		107 (225)	107 (225)	—	6.0	2	224	22	0.29	83
							3.0	3	250	6	0.12	25
		4.7		102 (215)	102 (215)	—	6.0	1	202	—	0.19	—
							3.0	3	197	8	0.10	75
		4.9		121 (250)	121 (250)	—	6.0	4	220	8	0.05	136
							3.0	3	219	9	0.09	97

*Cured specimens were dried to a constant weight at 121° C (250° F) prior to compaction. Uncured specimens were compacted at the plant temperature immediately following mixing.

**The number in parentheses is the number of specimens used to calculate Poisson's ratio.

1 N/cm² = 1.4504 psi

Static Test Results

Values of tensile strength, modulus of elasticity, and Poisson's ratio are summarized in Table 6 along with values previously reported by Adedimila and Kennedy for laboratory specimens (Ref 1) and Navarro and Kennedy for cores from inservice pavements (Ref 15).

As can be seen, the values obtained for dryer-drum mixtures were approximately the same as values obtained previously for conventional mixtures. Thus, in terms of static elastic and strength properties, the dryer-drum mixtures should perform as well as the inservice materials (Ref 15) and the laboratory-prepared specimens (Ref 1).

Repeated-Load Test Results

As reported by Adedimila and Kennedy (Ref 1), the relationship between permanent deformation and the number of load applications is linear between 10 to 80 percent of the fatigue life and, after an initial conditioning period, the modulus of elasticity decreases with an increase in the number of load applications. For this study, the elastic properties were determined at the 25th and 50th load cycles (Table 7) and at cycles corresponding to 30, 50, and 70 percent of fatigue life. Values for the 25th and 50th cycles were obtained for comparison purposes to determine whether acceptable values could be obtained after a limited number of cycles or loads. The values obtained for cycles corresponding to 30, 50, and 70 percent of fatigue life were averaged to obtain a mean value for the life of the mixture which can be compared to previously obtained mixture properties (Table 7). Table 5 summarizes these values and the coefficients of variation.

Instantaneous Resilient Modulus of Elasticity. Gonzalez et al (Ref 5) reported that the values of the instantaneous resilient modulus of elasticity at one percent of fatigue life would be 1.0 to 1.51 times larger than the modulus value at 50 percent of the fatigue life.

The relationships between the ratio of the values of instantaneous resilient modulus of elasticity for the 25th and 50th cycles to the value of the moduli at 50 percent of fatigue life and the percent of fatigue life are shown in Figs 17 through 21. As can be seen, the instantaneous resilient modulus of elasticity for the 25th cycle is in the range of 1.04 to 1.18 times the moduli at 50 percent of the fatigue life. For the 50th cycle, the

TABLE 6. COMPARISON OF STATIC STRENGTHS AND ELASTIC PROPERTIES

Type of Specimens	Tensile Strength, N/cm^2	Modulus of Elasticity, 10^3 N/cm^2	Poisson's Ratio	Source
Dryer-drum	42-102	56-183	0.14-0.42	—
Inservice cores	42-109	32-116	0.03-0.35	Ref 15
Laboratory specimens	100	80-136	0.08-0.20	Ref 1

Testing temperature = 23.9° C (75° F)

1 N/cm^2 = 1.4504 psi

TABLE 7. MEAN ELASTIC PROPERTIES UNDER REPEATED LOAD FOR THE 25TH AND 50TH CYCLES AND FOR THE MEAN OF THE CYCLES CORRESPONDING TO 30, 50, AND 70 PERCENT OF THE FATIGUE LIFE

District Project	Treatment	Mixing Temperature, °C (°F)	Compaction Temperature, °C (°F)	Applied Tensile Stress, N/cm²	Number of Specimens	Number of Cycles	% of N_f	Instantaneous Resilient Modulus of Elasticity, Mean, 10^3 N/cm²	Instantaneous Resilient Modulus of Elasticity, Mean, (10^3 psi)	Instantaneous Resilient Poisson's Ratio, Mean
8	Cured	—	Same as mixing	6.0	4	25	0.27	161	(234)	-0.05
						50	0.55	162	(235)	-0.06
						4,439	48.4	141	(205)	0.16
				3.0	5	25	0.05	137	(199)	-0.09
						50	0.11	143	(207)	-0.11
						23,717	51.3	128	(186)	0.07
	Uncured	—		6.0	5	25	0.24	166	(241)	0.00
						50	0.48	171	(248)	-0.01
						5,326	50.8	168	(244)	0.12
				3.0	5	25	0.07	156	(226)	-0.05
						50	0.14	161	(234)	-0.05
						17,721	50.4	143	(207)	0.07
11 (fine)	Cured	—	121 (250)	6.0	4	25	0.42	219	(318)	0.05
						50	0.83	227	(329)	0.05
						3,045	50.6	173	(251)	0.18
				3.0	6	25	0.11	193	(280)	-0.08
						50	0.22	203	(294)	-0.09
						11,259	50.6	189	(274)	0.13
	Uncured	—	Same as mixing	6.0	6	25	0.30	207	(300)	-0.02
						50	0.61	215	(312)	0.01
						4,077	49.5	184	(267)	0.17
				3.0	6	25	0.09	190	(276)	-0.06
						50	0.18	190	(276)	-0.07
						14,210	50.3	190	(276)	0.13
11 (coarse)	Cured	—	121 (250)	6.0	2	25	0.68	173	(251)	0.02
						50	1.35	174	(252)	0.04
						1,851	50.0	168	(244)	0.22
				3.0	2	25	0.29	175	(254)	-0.02
						50	0.59	183	(265)	-0.01
						4,303	50.6	151	(219)	0.21
	Uncured	—	Same as mixing	6.0	2	25	0.58	217	(315)	-0.05
						50	1.16	218	(316)	0.01
						1,424	33.0	184	(267)	0.12
				3.0	2	25	0.24	184	(267)	-0.05
						50	0.47	196	(284)	-0.05
						5,378	50.9	155	(225)	0.07
21	Cured	124 - 129 (255 - 265)	121 (250)	22.06	6	25	0.21	392	(569)	-0.09
						50	0.41	389	(564)	-0.08
						6,104	50.4	332	(482)	—
				5.52	7	25	0.008	260	(377)	-0.15
						50	0.02	266	(386)	-0.15
						194,843	62.0	266	(386)	0.17
	Uncured	124 - 129 (255 - 265)	124 - 129 (255 - 265)	22.06	6	25	0.96	389	(564)	-0.03
						50	1.93	398	(577)	-0.01
						1,296	49.9	349	(506)	0.12
				5.52	6	25	0.15	224	(325)	-0.10
						50	0.31	225	(326)	-0.09
						8,175	50.0	225	(326)	0.13
14	Uncured	96 (205)	96 (205)	6.0	2	25	0.08	324	(470)	0.20
						50	0.15	300	(435)	0.15
						15,242	47.2	276	(400)	0.27
				3.0	2	25	0.02	225	(326)	0.00
						50	0.04	211	(306)	-0.05
						69,075	49.4	213	(309)	0.17
	Uncured	96 (205)	96 (205)	6.0	2	25	0.08	284	(412)	0.09
						50	0.17	292	(424)	0.08
						13,932	49.9	224	(325)	0.29
				3.0	3	25	0.02	283	(410)	0.03
						50	0.03	282	(409)	0.05
						75,413	50.0	250	(363)	0.12
	Uncured	96 (205)	96 (205)	6.0	1	25	0.07	290	(421)	0.03
						50	0.13	287	(416)	0.05
						18,133	47.9	202	(293)	0.19
				3.0	3	25	0.04	215	(312)	-0.08
						50	0.07	208	(302)	-0.07
						33,787	47.9	197	(286)	0.10
	Uncured	96 (205)	96 (205)	6.0	4	25	0.07	253	(367)	-0.07
						50	0.14	250	(363)	-0.07
						17,153	48.8	220	(319)	0.05
				3.0	3	25	0.02	241	(350)	-0.03
						50	0.05	232	(336)	-0.03
						51,680	49.6	219	(318)	0.09

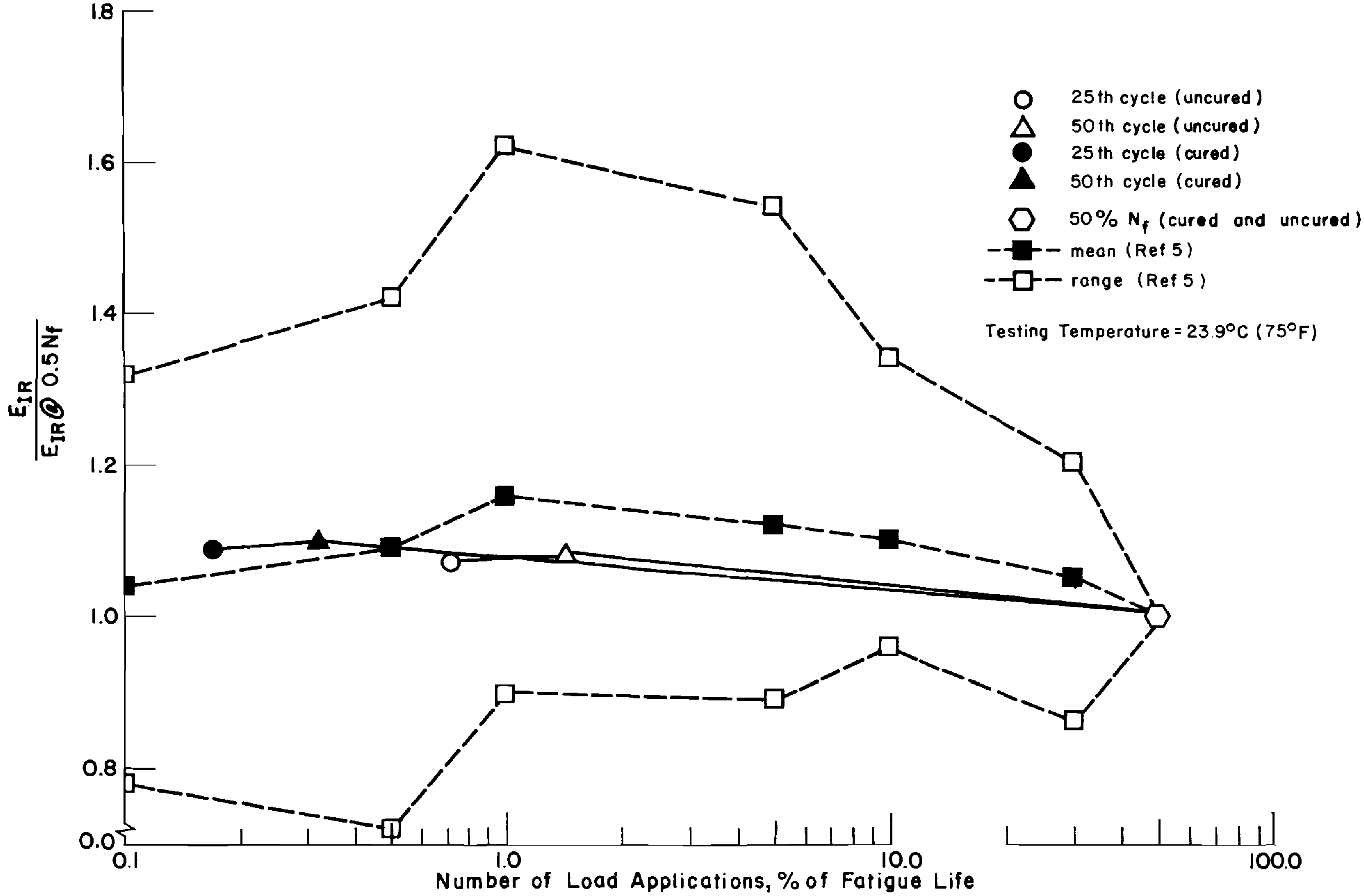


Fig 17. Relationship between instantaneous resilient modulus and number of load applications for Project 21.

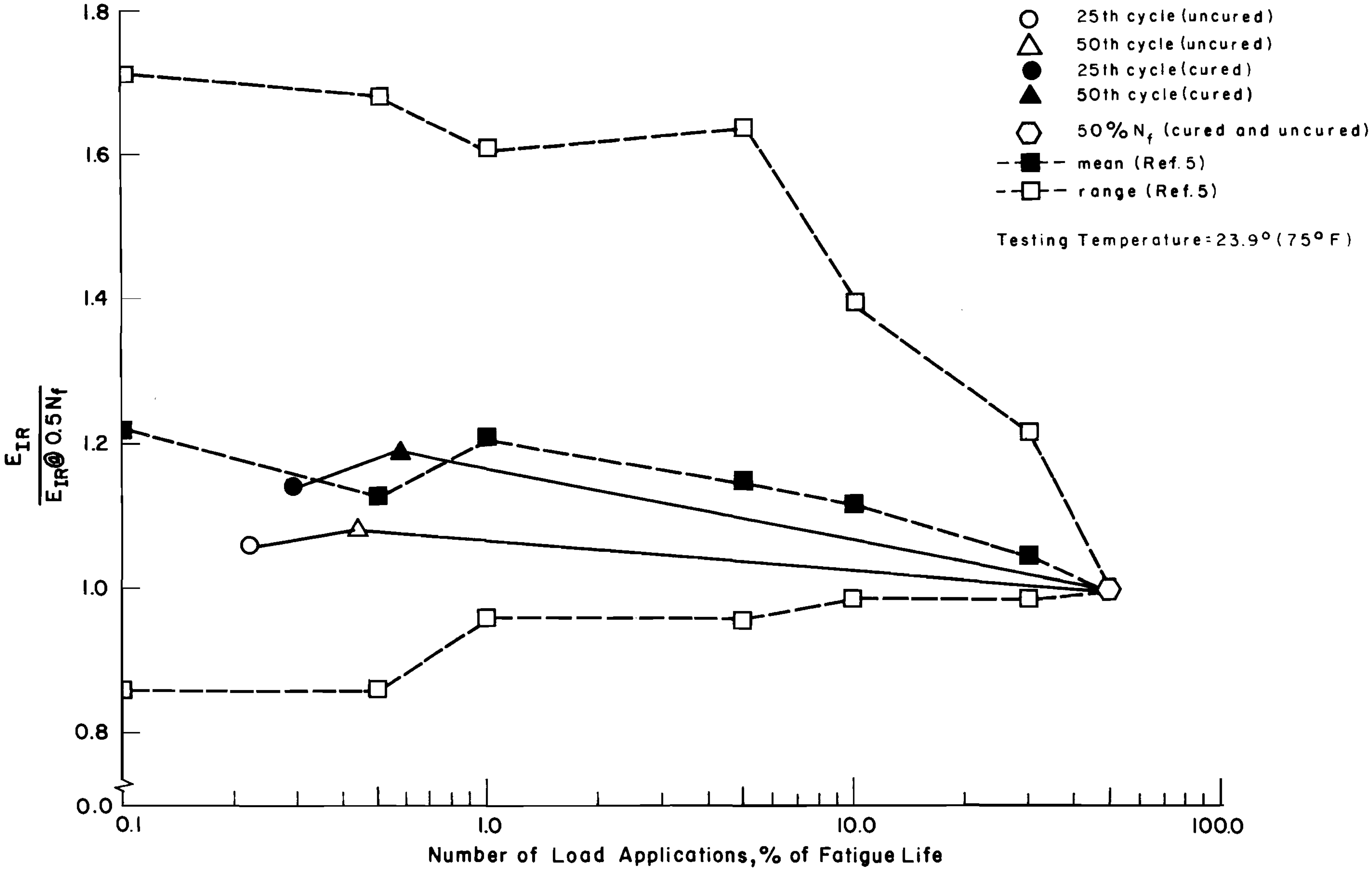


Fig 18. Relationship between resilient modulus and number of load applications for Project 11 (fine).

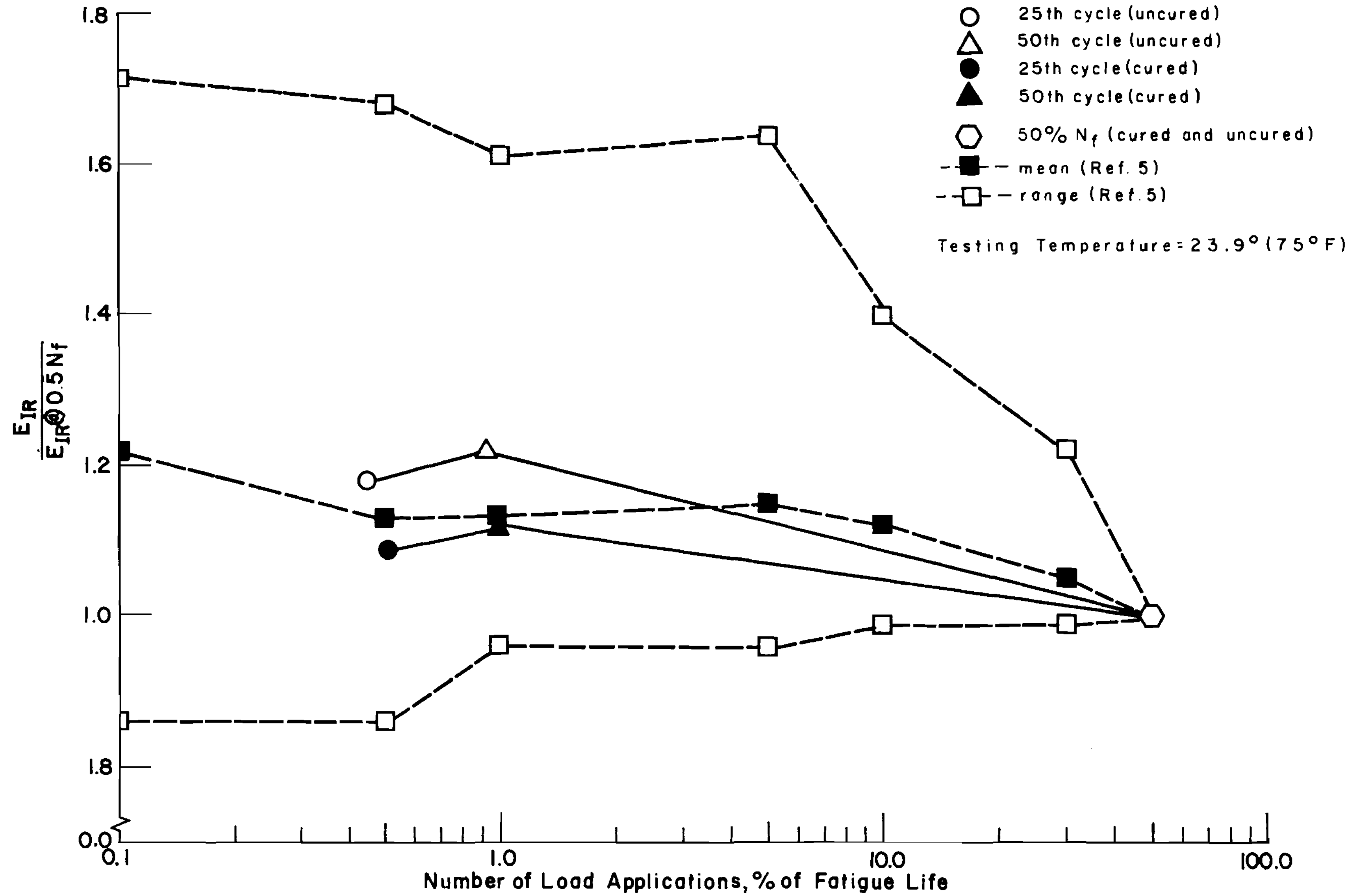


Fig 19. Relationship between resilient modulus and number of load applications for Project 11 (coarse).

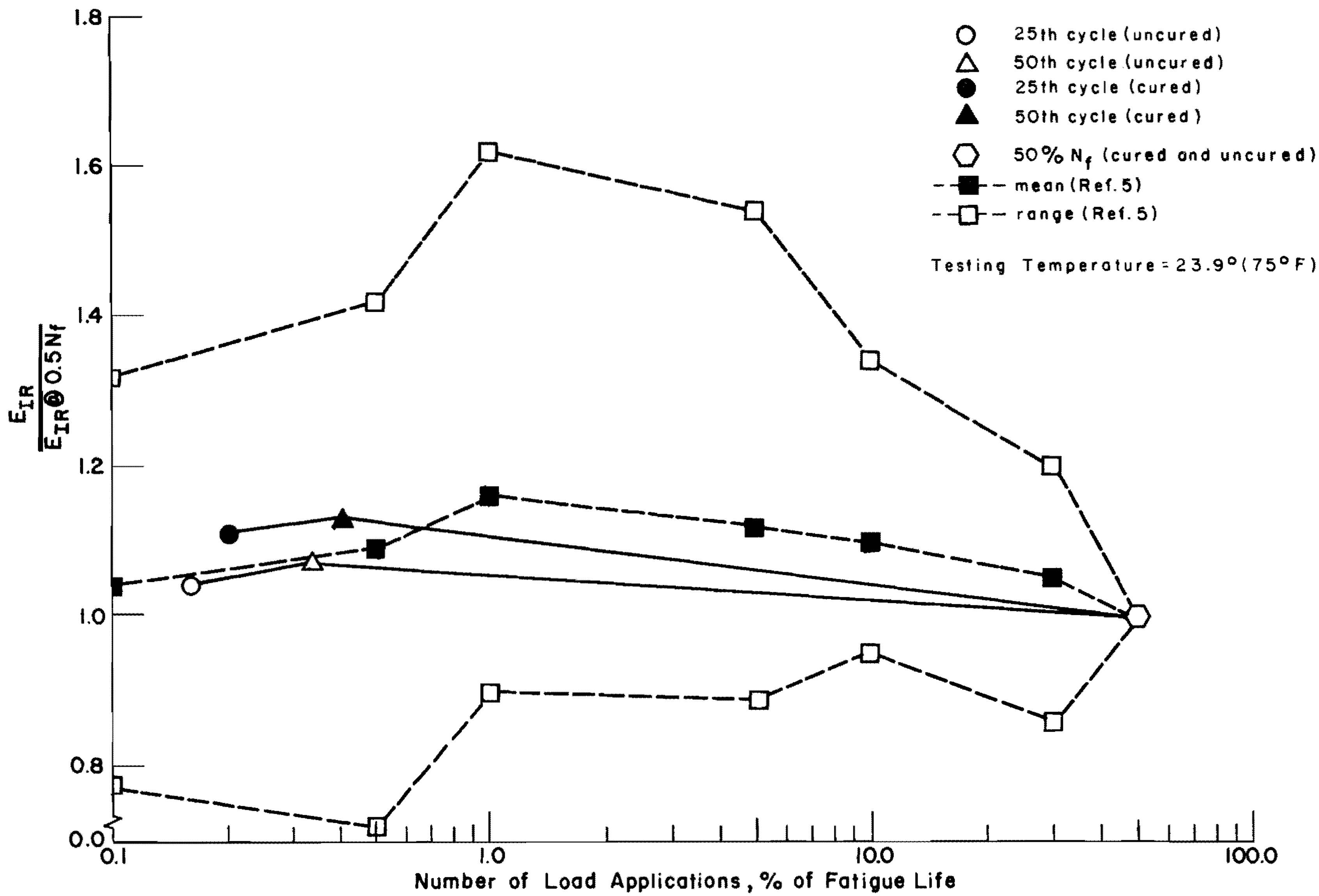


Fig 20. Relationship between resilient modulus and number of load applications for Project 8.

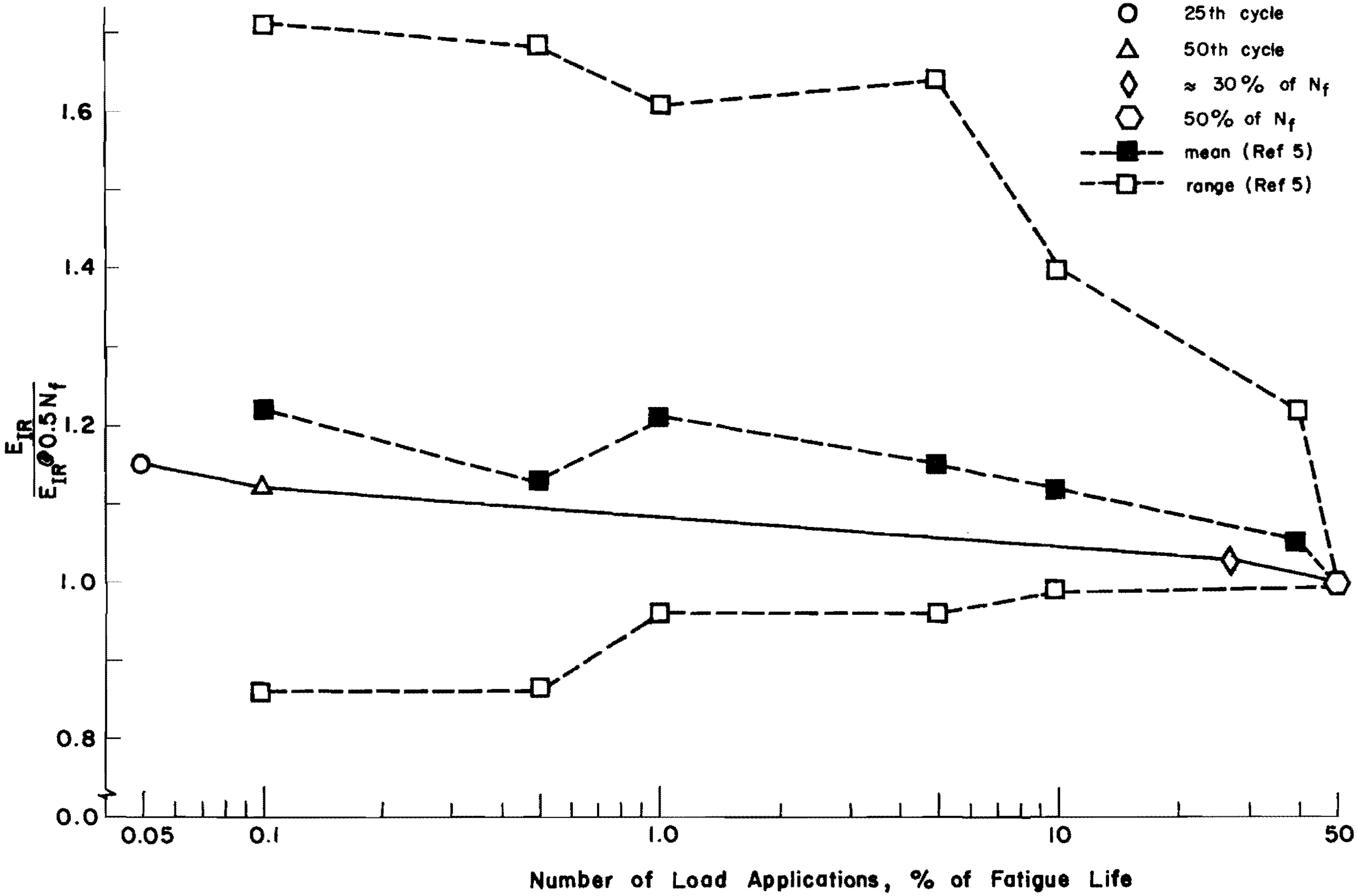


Fig 21. Relationship between instantaneous resilient modulus and number of load applications for Project 14.

values of the moduli range from 1.07 to 1.22 times the moduli at 50 percent of the fatigue life. In the same figures are shown the mean and range of values previously reported by Gonzalez et al (Ref 5). As can be seen, the values reported in this study are in the range previously reported and are very close to the mean value. Thus, it appears that the resilient modulus of elasticity can be obtained after 25 load cycles but it is recommended that 50 cycles be used to insure stability.

Even though the values of the instantaneous resilient modulus of elasticity seem approximately the same for the 25th cycle, the 50th cycle, and the average of the values obtained at the cycles corresponding to 30, 50, and 70 percent of the fatigue life, all the analysis was done with the average value, since this was the value previously used and reported by Navarro and Kennedy (Ref 15) for inservice asphalt mixtures produced using a conventional plant.

The mean and the coefficients of variation of the values of the instantaneous resilient modulus of elasticity for each project, treatment, and stress are shown in Table 5. The values of the mean ranged from 128×10^3 to 349×10^3 N/cm^2 (186×10^3 to 506×10^3 psi) with the coefficient of variation ranging from 4 to 25 percent. Navarro and Kennedy (Ref 15) reported values of modulus for mixes produced with a conventional plant ranging from 152×10^3 to 424×10^3 N/cm^2 (220×10^3 to 615×10^3 psi) with a coefficient of variation ranging from 4 to 28 percent. For both studies, the moduli were consistent within each project; therefore, the coefficients of variation for each project were small. Thus, the moduli obtained for dryer-drum mixtures tested in this study were essentially equal to those reported in previous studies of conventional mixtures.

Instantaneous Resilient Poisson's Ratio. The instantaneous resilient Poisson's ratios were not well defined at the 25th and 50th cycles and in many cases were negative. Thus, only the average values, i.e., the mean of the values obtained for load cycles corresponding to 30, 50, and 70 percent of the fatigue life, were considered. These mean values ranged from 0.05 to 0.38 (Table 5), with the larger values occurring at the high stress levels. Previously reported values (Ref 15) of instantaneous resilient Poisson's ratio for field cores of asphalt concrete mixes produced by the conventional plant were 0.44 and 0.57. Adedimila and Kennedy (Ref 1) reported values of instantaneous resilient Poisson's ratio at 24° C (75° F) for laboratory-prepared specimens of asphalt concrete ranging from 0.04 to 0.20. Thus, the values of the instantaneous resilient Poisson's ratio found in this study, even though they were generally smaller, were within the range of values previously reported for conventional plants.

EFFECT OF CURING TREATMENT

As summarized in Tables 3, 4, and 5 and illustrated in Figs 16 through 22, there generally were no differences in the elastic and fatigue properties for the cured and uncured specimens. The only exception was District 21, for which the static tensile strength and the fatigue life were higher for the cured specimens.

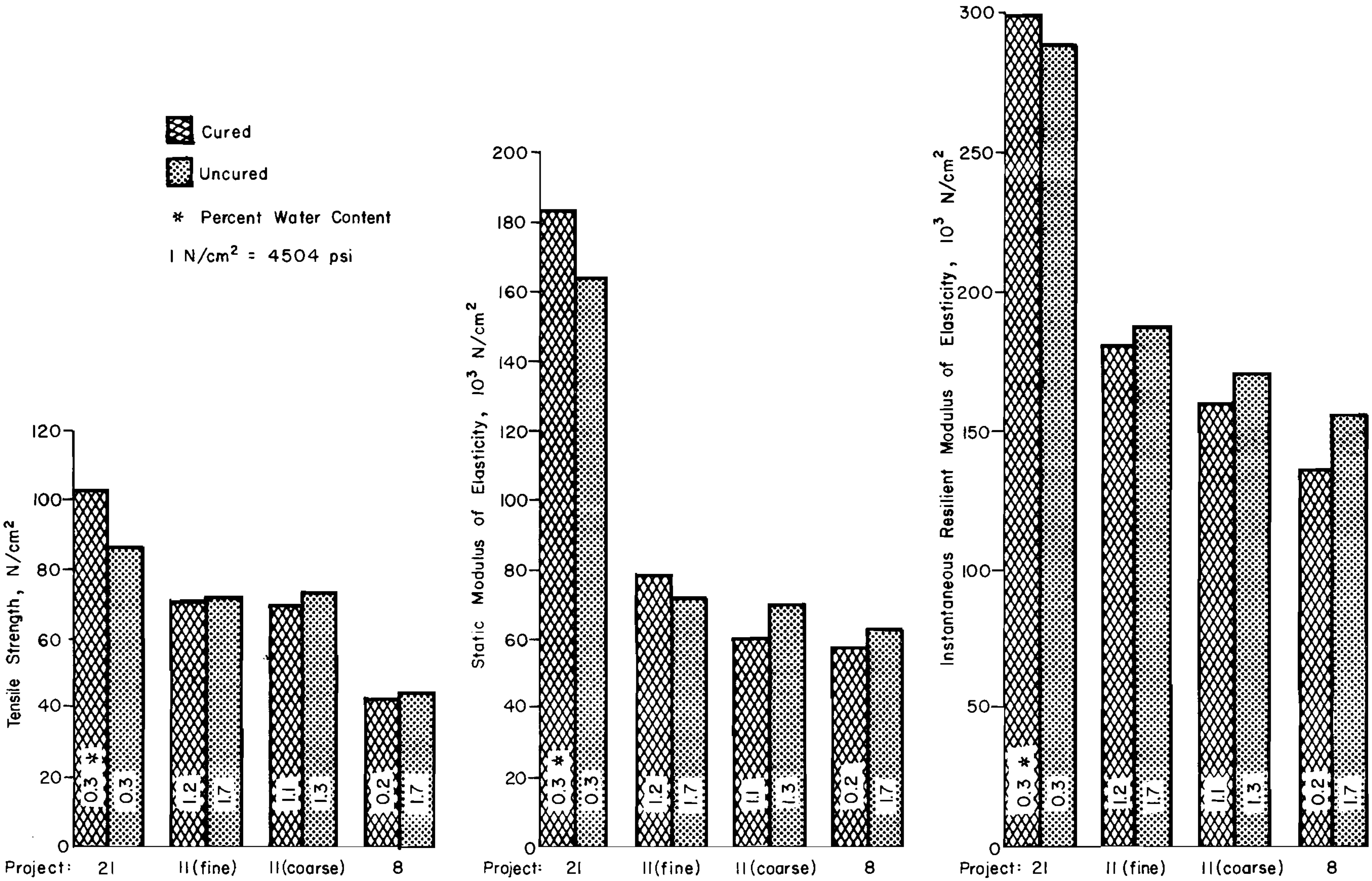
EFFECT OF MIX TEMPERATURE

An evaluation of the effect of the mixing temperature on the fatigue and elastic properties was made by testing specimens from District 14. The specimens were produced at four different mix temperatures and asphalt contents in the dryer-drum plant.

Static Results

The values of the mean and the coefficients of variation of the static tensile strength, static modulus of elasticity, and static Poisson's ratio for each temperature are summarized in Table 4. The relationships of these properties with the mix temperature are shown in Fig 23. Hadley et al (Ref 8) found that the tensile strength increased significantly with an increase in mixing temperature. A more recent study (Ref 9) showed that mix temperature did not affect the tensile strength. As can be seen in Fig 23a, an increase in mixing and compaction temperature caused a small decrease in the tensile strength. The increments in the mixing and compaction temperature in this study, however, were smaller than used in previous studies and also involved different asphalt contents.

The static modulus of elasticity and the static Poisson's ratio (Figs 23b and 23c) did not show significant change with a change in mix temperature. Previously Hadley et al (Ref 9) also reported that mixing temperature did not significantly affect the static elastic properties.

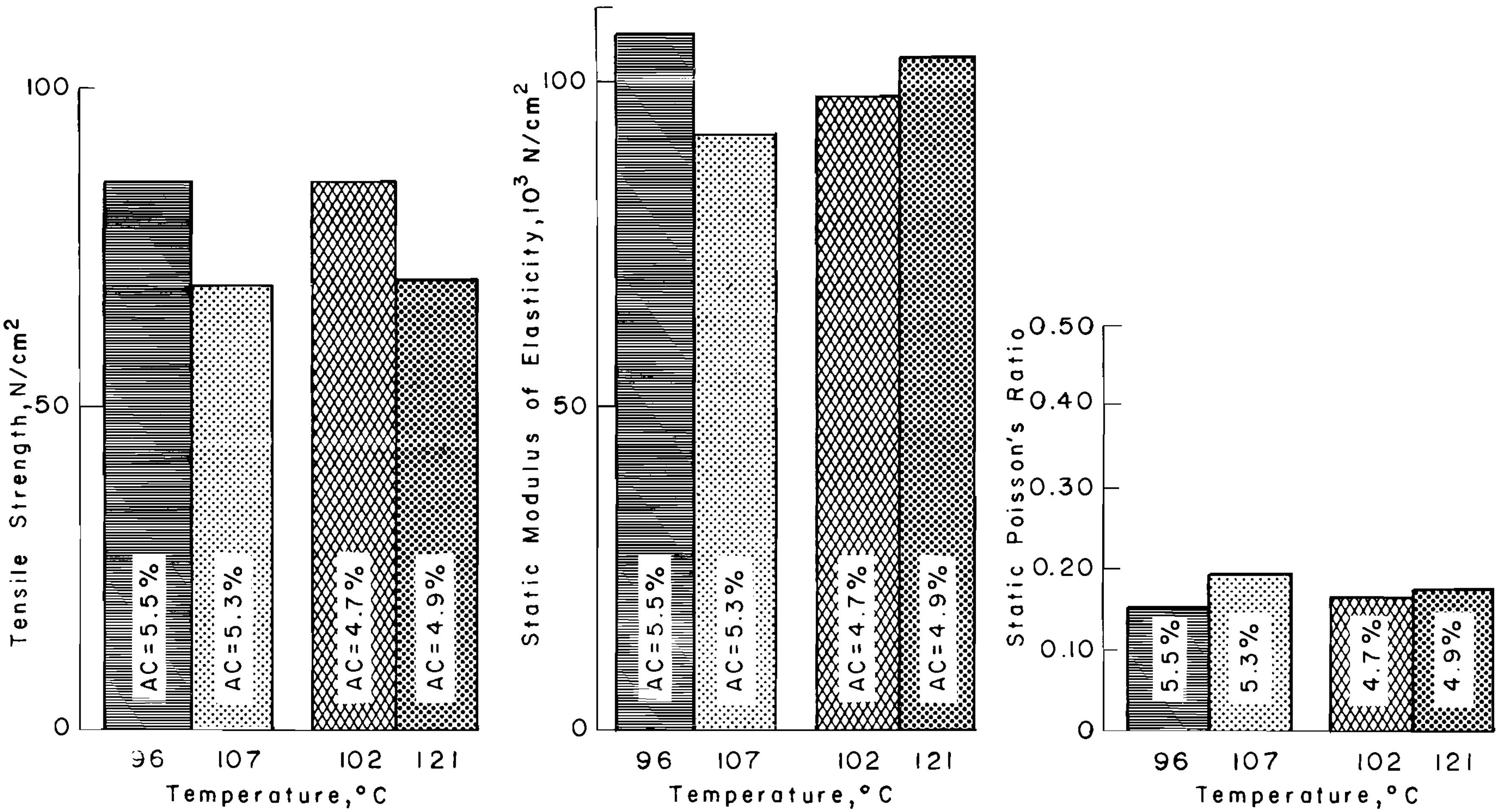


(a) Tensile strength.

(b) Static modulus of elasticity.

(c) Instantaneous resilient modulus of elasticity.

Fig 22. Effect of curing treatment on engineering properties.



(a) Tensile strength. (b) Static modulus of elasticity. (c) Static Poisson's ratio.

Fig 23. Effect of mixing temperature on engineering properties of Project 14.

Fatigue Results

The properties evaluated were fatigue life, instantaneous resilient modulus of elasticity, and Poisson's ratio.

The values of the mean and the coefficient of variation of fatigue life and the values of K_2' , n_2 , and R^2 are summarized in Table 3. As can be seen in Fig 24, the values of n_2 and K_2' were approximately equal for the group of specimens produced with 5.5 percent asphalt content at 96° C (205° F) and those produced with 5.3 percent asphalt content at 107° C (225° F). Nevertheless, there were significant differences in the values of n_2 and K_2' for the mixtures containing 4.7 and 4.9 percent asphalt and mixed at 102° C (215° F) and 121° C (250° F), respectively. Moore and Kennedy (Ref 11) reported small differences in the fatigue life for materials mixed at different temperatures.

Table 5 contains the values of the mean and the coefficient of variation of the instantaneous resilient modulus of elasticity and the instantaneous Poisson's ratio. No consistent change in the value of the modulus was observed with a change in mix temperature (Fig 25a). The instantaneous Poisson's ratio decreased with an increase in mix temperature and the change was significant at the lower asphalt content (Fig 25b).

CORRELATIONS

Previous studies on conventional asphalt mixtures have shown correlations between

(1) fatigue life and tensile strain,

(2) fatigue life and stress-strength ratio, and

(3) the fatigue constants n_2 and K_2' .

Fatigue Life - Tensile Strain Relationship

Previous investigators have shown that fatigue life is related to strain (Ref 11). Saal and Pell (Ref 17) found the relationship between the logarithm of strain and the logarithm of fatigue life was linear for constant stress loading. Navarro and Kennedy (Ref 15) evaluated the relationship between fatigue life and tensile strain for field core specimens. A definite relationship was established, indicating that a great deal of variation would be

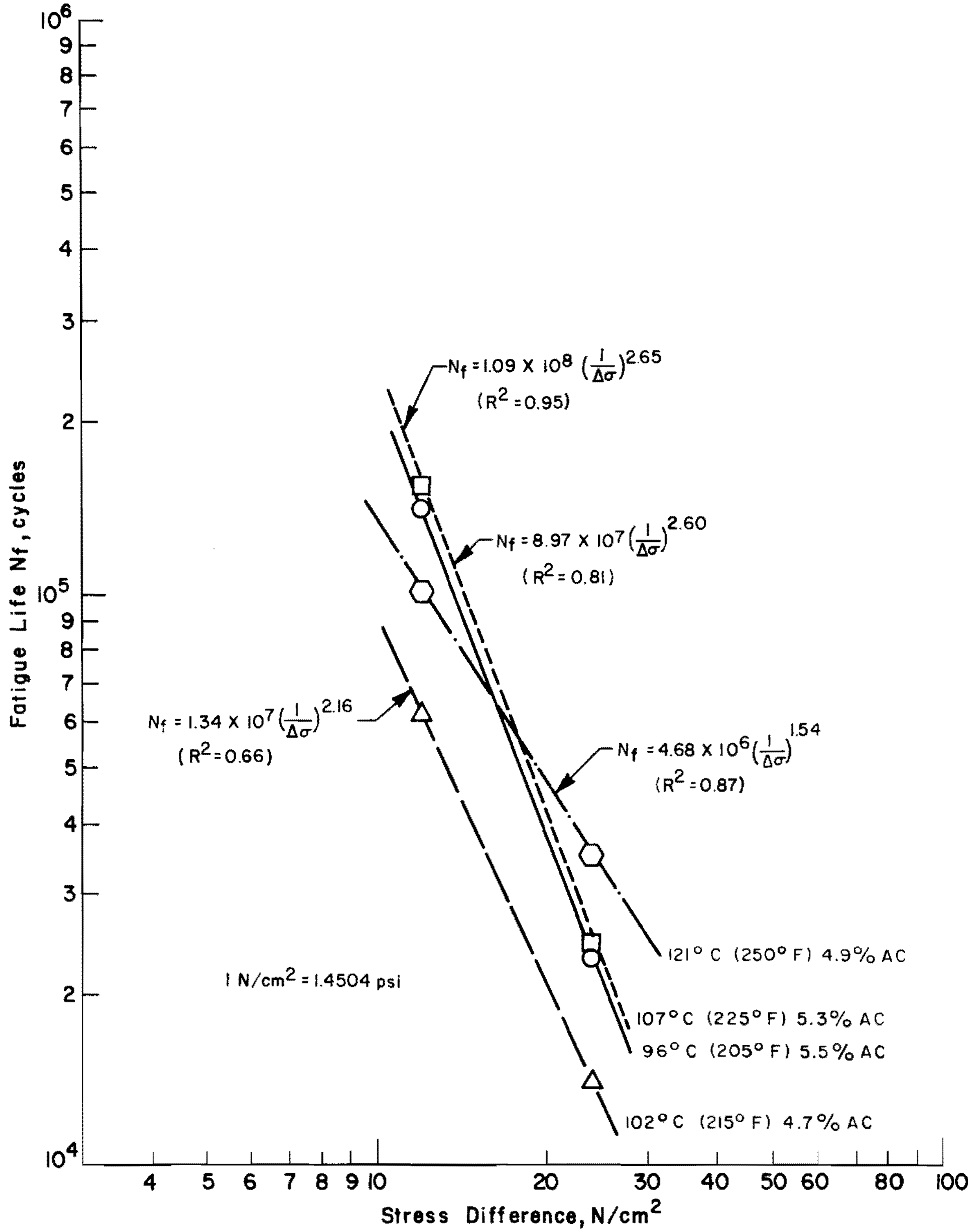


Fig 24. Relationship between the logarithms of fatigue life and stress differences for different mixing temperatures for Project 14.

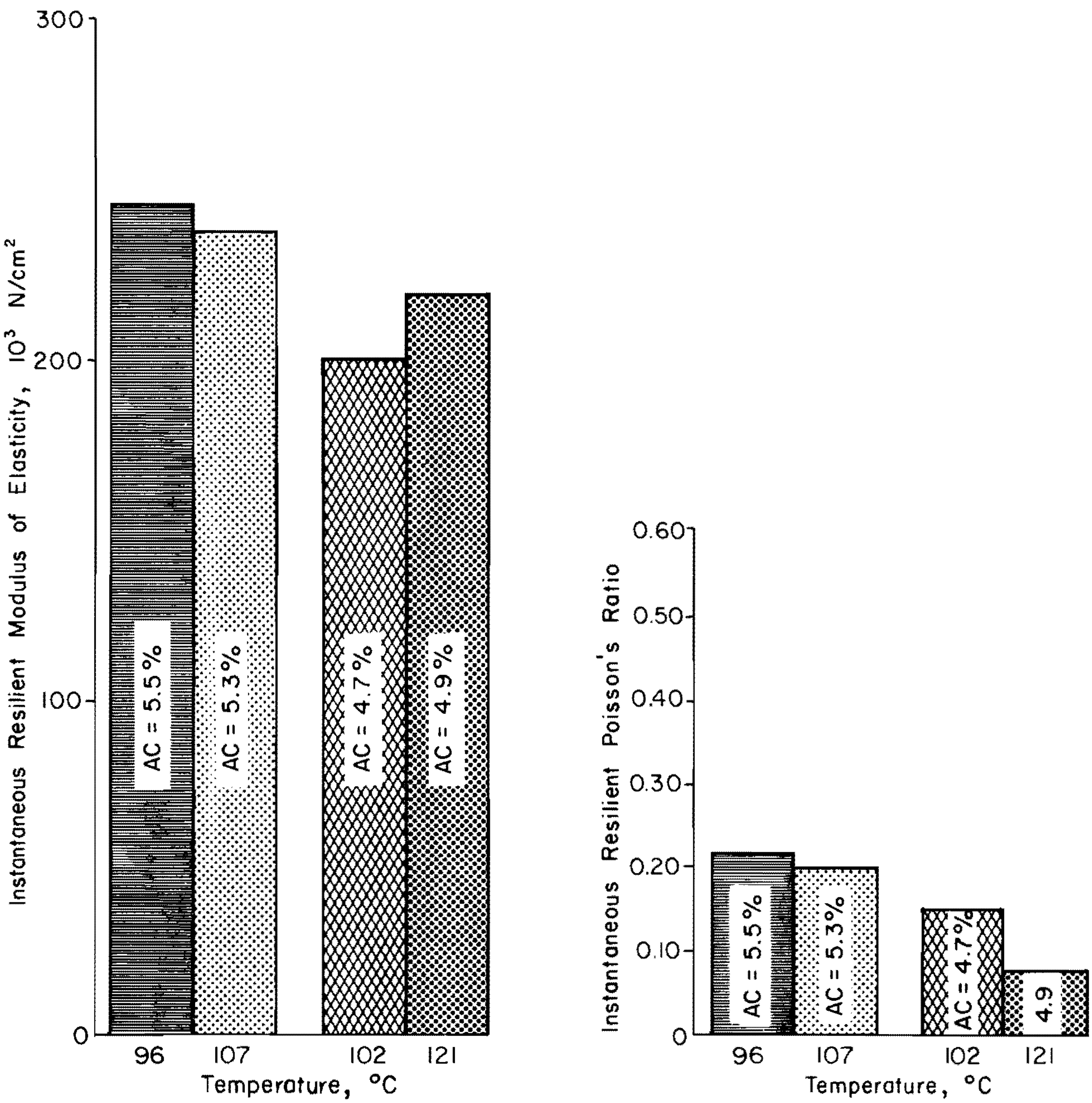


Fig 25. Effect of mixing and compaction temperature on resilient properties of Project 14.

accounted for by the relationship but that substantial estimation errors could be expected if the relationship were used to predict fatigue life.

The relationships between fatigue life and the tensile strain for the 25th cycle and the average tensile strain, i.e., the mean of the strains for cycles corresponding to 30, 50, and 70 percent of fatigue life, are shown in Fig 26. Tensile strains were estimated by dividing the tensile stress σ_T by the instantaneous resilient modulus of elasticity E_{IR} . As shown, the coefficients of determination R^2 for both relationships were 0.40, indicating that very little of the variation could be accounted for by the linear relationship; thus, these relationships should not be used to estimate fatigue life. Also, it can be seen that the values of n_1 and K_1 for the relationship with the tensile strain calculated for the 25th cycle were almost the same as those with the tensile strain calculated at the mean of 30, 50, and 70 percent of fatigue life.

Previous studies (Refs 11 and 12) indicate that the fatigue life can be predicted in terms of initial strain. Adedimila and Kennedy (Ref 1) evaluated the relationship between the fatigue life and the initial strain defined as the ratio of the repeated tensile stress to the static modulus of elasticity. This relationship (Fig 26) with a coefficient of determination of 0.70 is considered to be relatively accurate even though some error could be expected if the relationship is used to estimate fatigue life. The relationship of fatigue life and initial strain evaluated for mixtures produced by the dryer-drum plant is shown also in Fig 26. A coefficient of determination of 0.60 indicates a relatively weak correlation. Thus the fatigue life - initial strain relationship is better than the fatigue life - tensile strain relationship for estimating fatigue life.

Stress-Strength Ratio

Previous studies have indicated that the relationship between fatigue life and the stress-strength ratio can be used to estimate fatigue life. Navarro and Kennedy (Ref 15) evaluated this relationship for field cores and Adedimila and Kennedy (Ref 1) also evaluated the relationship between fatigue life and the stress-strength ratio for laboratory-processed specimens. The relationship between fatigue life and stress-strength ratio for this study is shown in Fig 27, along with the relationships found by Navarro and Kennedy and Adedimila and Kennedy.

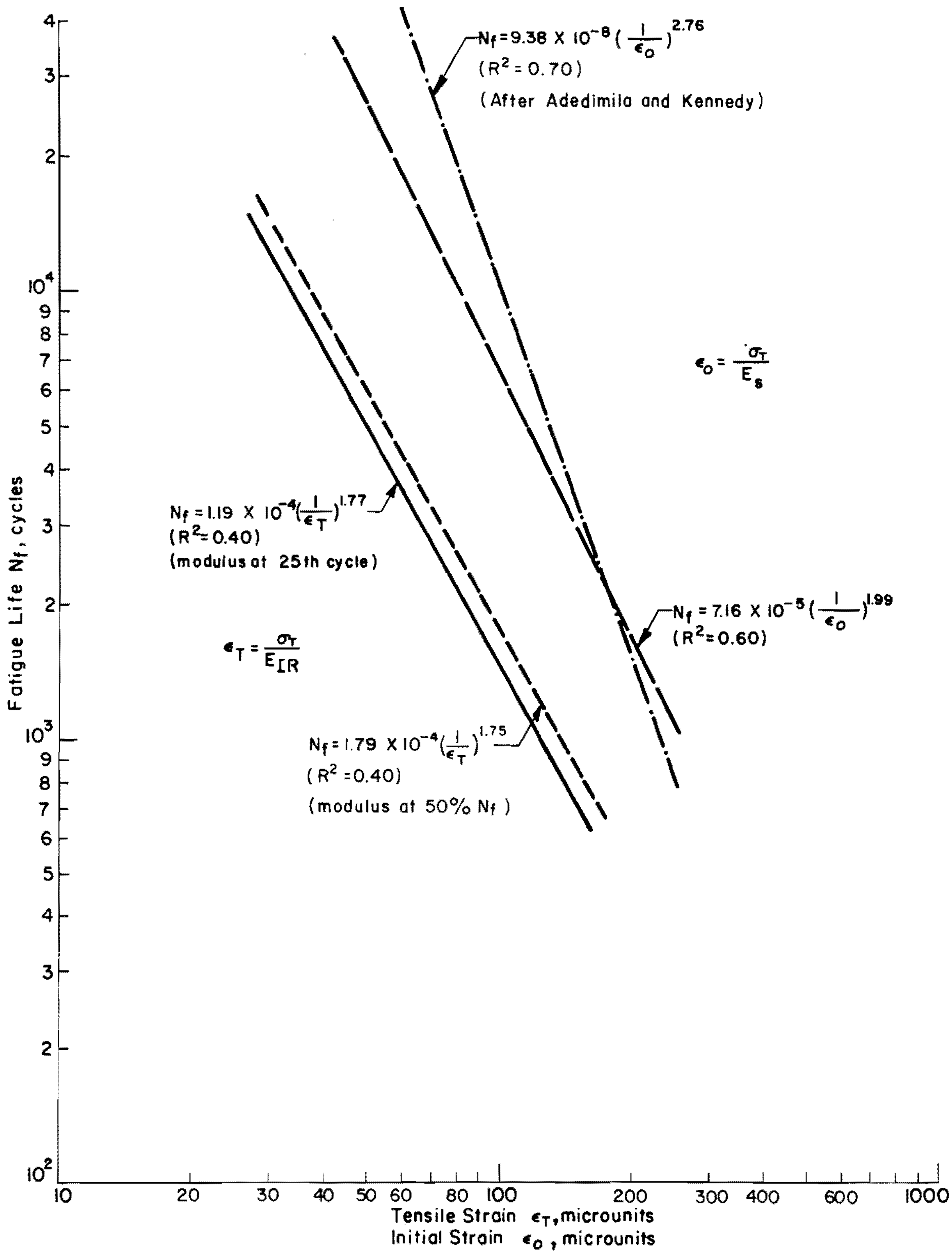


Fig 26. Relationships between fatigue life and strain for Project 14.

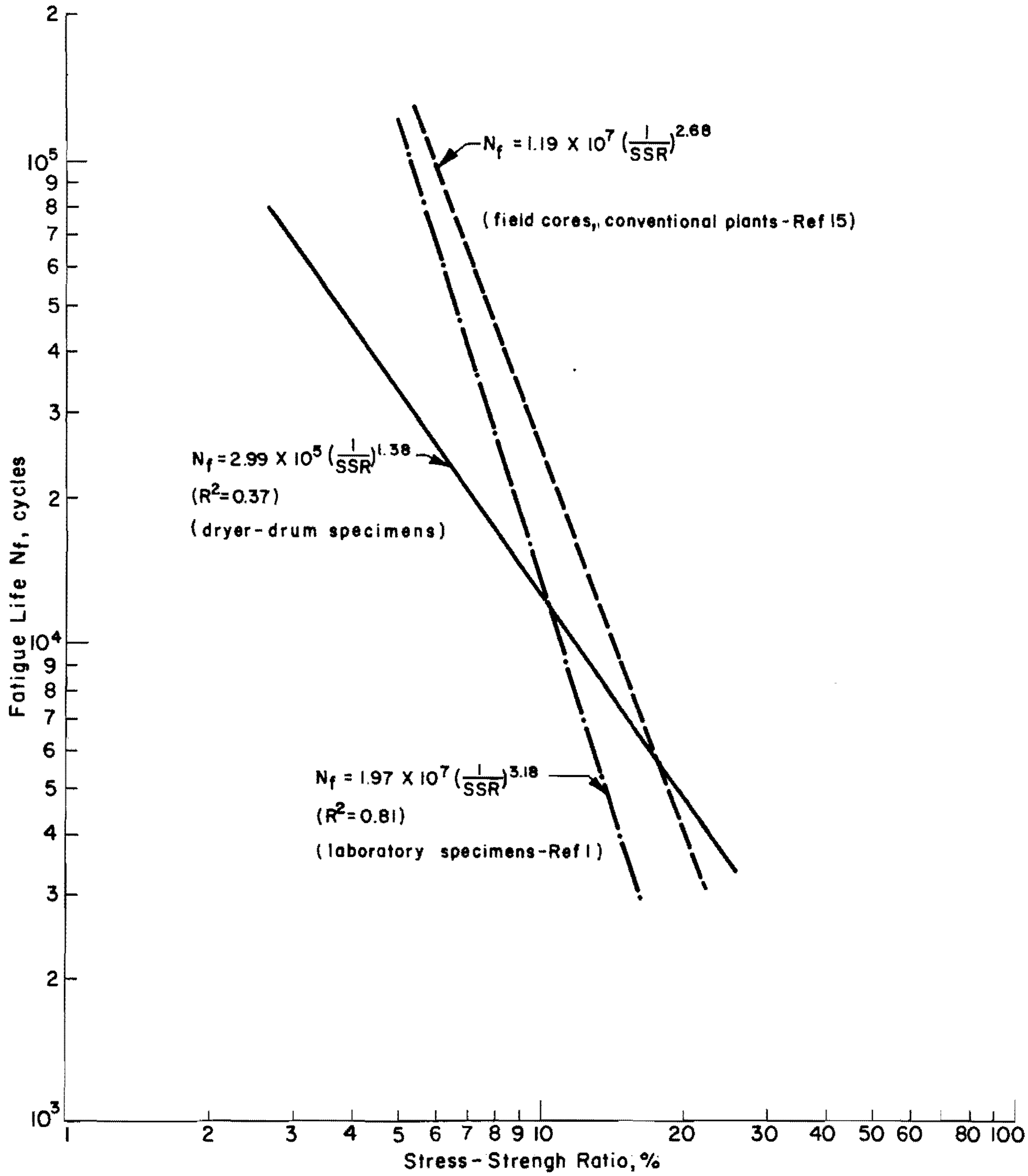


Fig 27. Logarithmic relationships between fatigue life and stress-strength ratio.

The coefficient of determination R^2 for the present study was 0.37. This small coefficient shows a very poor correlation, which possibly can be attributed to the fact that the instantaneous resilient moduli of elasticity were different for each project.

The relationship for the laboratory-processed specimens had a large coefficient of determination, indicating that the relationship could be used for estimating fatigue lives. The use of the relationships for this study and for cores of conventional mixtures is not recommended since large errors can be expected.

Relationship Between n_2 and K_2'

Adedimila and Kennedy (Ref 1) found that a linear relationship exists between n_2 and the logarithm of K_2', which can be expressed in the general form

$$n_2 = A_2 + B_2 \log K_2'$$

with n_2 as a dependent variable, or

$$\log K_2' = C_2 + D_2 n_2$$

with $\log K_2'$ as a dependent variable.

The relationships obtained for this study were

$$n_2 = -1.145 + 0.4517 \log K_2'$$

$$(R^2 = 0.83 , S_e = 0.21)$$

and

$$\log K_2' = 3.233 + 1.8487 n_2$$

$$(R^2 = 0.83 , S_e = 0.43)$$

Figure 28 illustrates the relationship between n_2 and K_2' obtained for this study, along with those obtained by Adedimila and Kennedy (Ref 1) and Navarro and Kennedy (Ref 15). The relationships obtained in this study had a fairly high coefficient of determination although not as high as those reported in previous studies.

A regression analysis was conducted on all the data for the three studies to obtain a single relationship. The resulting relationships were (Fig 29)

$$n_2 = -0.566 + 0.4013 \log K_2'$$
$$(R^2 = 0.90 \, , \; S_e = 0.33)$$

and

$$\log K_2' = 2.099 + 2.261 \, n_2$$
$$(R^2 = 0.90 \, , \; S_e = 0.79)$$

Because of the high coefficient of determination obtained for the combination, it is felt that a relationship exists between n_2 and K_2' and that the relationship is consistent with the relationships previously reported (Ref 1).

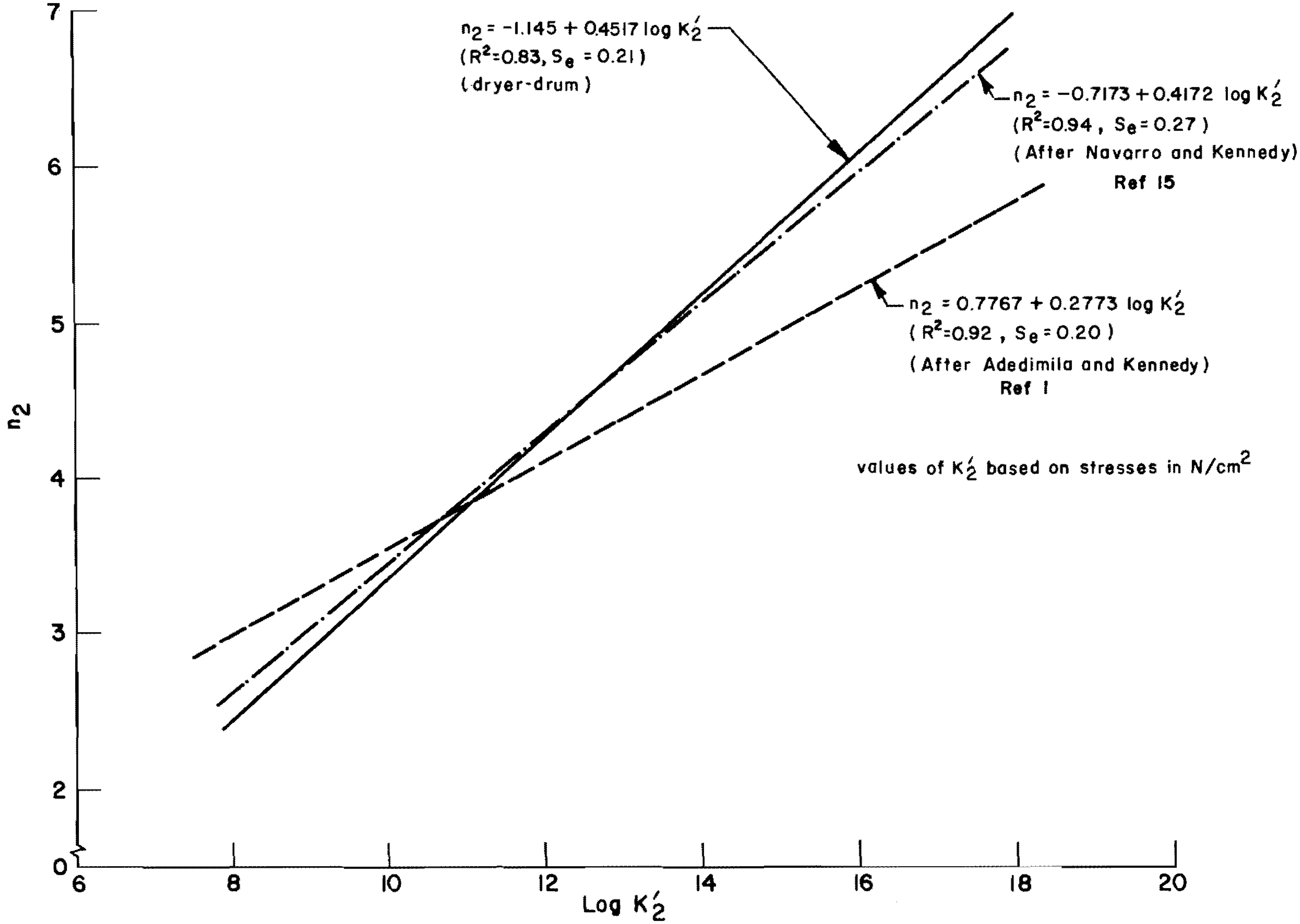


Fig 28. Relationship between n_2 and $\log K_2'$ for various studies.

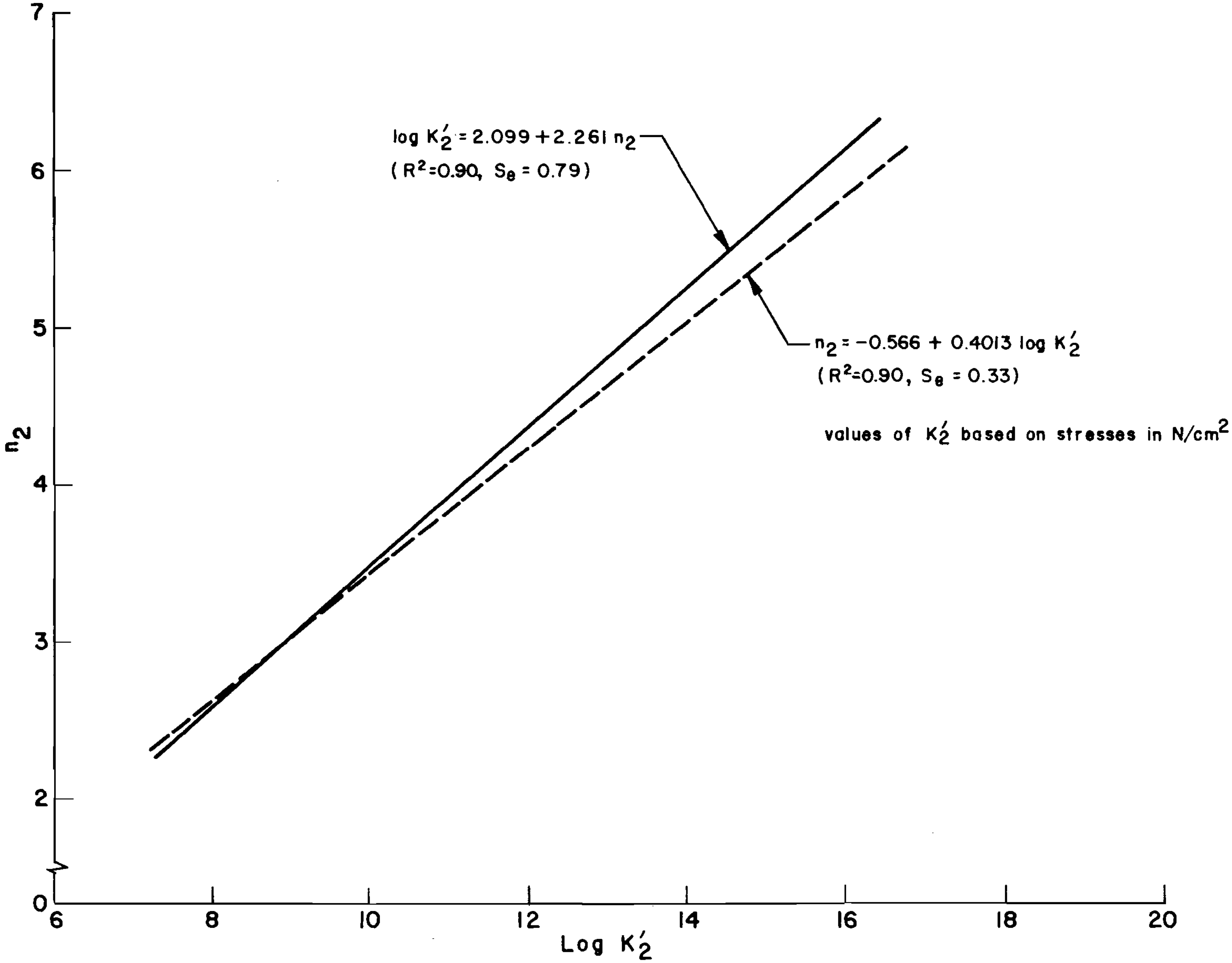


Fig 29. Combined relationships between n_2 and $\log K_2'$ for various studies.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the findings of a study to evaluate the fatigue and elastic properties of asphalt mixtures produced using a dryer-drum plant. Included is a comparison of these properties with the properties of asphalt mixtures produced by a conventional plant. Mixtures with high moisture content were not available; therefore, effects of moisture could not be evaluated. Factors which could be evaluated were curing treatment and mixing-compaction temperature. It should be noted that all specimens were field mixed and laboratory compacted. The conclusions and recommendations from this study are summarized below.

COMPARISON WITH CONVENTIONAL MIXTURES

General

(1) The engineering properties of the dryer-drum mixtures evaluated in this study generally were equal to those of previously evaluated inservice and laboratory-prepared mixtures. The one exception was fatigue life, which appeared to be less for the dryer-drum mixtures.

(2) Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced with the dryer-drum. The only question relates to the effect of moisture and it would appear from previous experience that moisture produces little if any adverse effect. Additional study, however, is needed.

Fatigue Life

(1) The relationships between the logarithm of fatigue life and the logarithm of stress difference were essentially linear and could be expressed as

$$N_f = K_2'\left(\frac{1}{\Delta\sigma}\right)^{n_2}$$

where

N_f = fatigue life, cycles,

$\Delta\sigma$ = stress difference, N/cm^2 ,

K_2' = material constant, the antilog of the intercept value of the logarithm relationship between fatigue life and stress difference, and

n_2 = material constant, the absolute value of the slope of the logarithm relationship between fatigue life and stress difference.

(2) Values of n_2 were fairly constant, ranging from 1.24 to 2.28. These values were low compared to previously reported values for field cores of mixtures produced using a conventional plant.

(3) Values of K_2' ranged from 7.05×10^5 to 2.52×10^8 . These values were also small compared to previously reported values for mixtures produced using conventional plants.

(4) The fatigue lives of the dryer-drum mixtures were generally smaller than those of previously studied conventional mixtures.

(5) The coefficients of variation of fatigue life ranged from 2 to 82 percent; these values are generally lower than those previously reported.

Strength and Static Elastic Properties

(1) The tensile strengths, static modulus of elasticity, and static Poisson's ratio are comparable to those previously reported for mixtures produced using a conventional plant.

(2) Tensile strength varied from 42 to 102 N/cm^2 (61 to 148 psi); static modulus of elasticity ranged from 56×10^3 to 183×10^3 N/cm^2 (81×10^3 to 265×10^3 psi); and Poisson's ratio values ranged from 0.14 to 0.42.

Repeated-Load Elastic Properties

(1) The instantaneous resilient modulus of elasticity ranged from 128×10^3 to 349×10^3 N/cm^2 (186×10^3 to 506×10^3 psi). These values were essentially equal to those reported in previous evaluations of conventional mixtures.

(2) The mean resilient Poisson's ratio values ranged from 0.07 to 0.38 and were slightly smaller than those previously reported for conventional mixtures.

(3) Reasonable estimates of the modulus could be obtained at the 25th and 50th cycles.

(a) The values of the instantaneous resilient modulus of elasticity for the 25th cycle were in the range of 1.04 to 1.18 times the new instantaneous resilient modulus at 50 percent of fatigue life.

(b) The values of the instantaneous resilient modulus for the 50th cycle were in the range of 1.07 to 1.22 times the modulus at 50 percent of fatigue life.

(4) The instantaneous resilient Poisson's ratios were not well defined at the 25th and 50th cycles and in many cases were negative.

EFFECT OF CURING TREATMENT

There generally were no differences in the elastic and fatigue properties of the cured and the uncured specimens. The only exception was for Project 21, for which the tensile strength and the fatigue life were higher for the cured specimens. These differences are possibly due to the fact that the type of asphalt used in Project 21 was different from that used in the others.

EFFECT OF MIX TEMPERATURE

Static Results

(1) An increase in the mixing-compaction temperature caused a small decrease in the tensile strength. Previously reported values indicated that mix temperature did not affect the tensile strength, but that increased compaction temperatures produced larger tensile strength.

(2) The static modulus of elasticity and the static Poisson's ratio did not show significant change with a change in mix temperature. Previous studies reported no variation in the same properties.

Repeated-Load Results

(1) The values of n_2 and K_2' were very similar for the specimens produced at 5.5 percent of asphalt content at 96° C (205° F) and those produced at 5.3 percent of asphalt at 107° C (225° F).

(2) Significant differences in the values of n_2 and K_2' were observed from the groups processed with 4.7 and 4.9 percent of asphalt at 102° C (215° F) and 121° C (250° F), respectively.

(3) No consistent change in the resilient modulus was observed with a change in the mixing-compaction temperature.

(4) The resilient Poisson's ratio decreased with an increase in the mixing-compaction temperature.

CORRELATIONS

(1) A correlation between the logarithm of fatigue life and the logarithm of tensile strain was found to exist. However, this relationship should not be used to predict fatigue life because of the relatively large errors which could be expected.

(2) Relatively weak correlations were found to exist between the logarithms of fatigue life and strain; the better correlation was for the relationship between fatigue life and initial strain.

(3) A correlation between fatigue life and the ratio of repeated tensile stress to static tensile strength was found to exist; however, large errors would be expected if it were used to predict fatigue life. More important is the fact that the relationship was much different from the relationships obtained for other types of mixtures.

(4) There was a linear relationship between n_2 and the logarithm of K_2'. Such a relationship can simplify fatigue life predictive equations by reducing the number of constants associated with them.

RECOMMENDATIONS

(1) It is recommended that the dryer-drum process be used for the production of asphalt mixtures.

(2) Additional research probably should be conducted specifically to address the question of the effect of moisture on dryer-drum mixtures. An attempt should be made to determine how much moisture is present and the magnitude of its effects.

(3) Studies should be conducted on specimens consisting of the same kind of aggregates, asphalt type, and asphalt content but mixed using the two processes, in order to establish a realistic comparison between dryer-drum and conventional plants.

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