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This report summarizes the results of an investigation of the resilient elastic and fatigue behavior of inservice concrete from pavements in Texas. Static indirect tensile tests were conducted in order to estimate the average tensile strength of each of the four projects tested. Repeated-load indirect tensile tests were conducted to determine the fatigue and resilient characteristics and the relationship between fatigue life and stress/strength ratio.

Deformation measurements were taken during fatigue testing in order to determine the resilient elastic properties of the material and the changes in these properties during the test period. In addition, estimates of the variation in fatigue life and elastic properties were made.

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FATIGUE AND REPEATED-LOAD ELASTIC CHARACTERISTICS OF INSERVICE PORTLAND CEMENT CONCRETE

by

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Research Report Number 183-9

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
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

June 1977

PREFACE

This is the ninth in a series of reports dealing with the findings of a research project concerned with tensile and elastic characteristics of highway pavement materials. This report summarizes the results of a study to determine the fatigue and elastic characteristics of inservice portland cement concrete pavement in Texas. Changes in the elastic properties which occur as the number of load applications increases were studied and estimates of the variations that occur in the fatigue and elastic properties were made. In addition, attempts were made to correlate fatigue life and tensile strength in order to provide a means of estimating fatigue behavior from strength results.

This report would not have been possible without the help and assistance of many people. Special appreciation is due James N. Anagnos and Pat S. Hardeman for their assistance in the testing program and Avery Smith, Gerald Peck, and James L. Brown, of the Texas State Department of Highways and Public Transportation, who provided technical liaison for the project. Appreciation is extended to District Laboratory Engineers David Bass, Robert E. Long, and John Betts, who supplied the materials tested in this study. Thanks are also extended to Larry G. Walker, Materials and Tests Engineer, for his cooperation in this project. The support of the Federal Highway Administration, Department of Transportation, is gratefully acknowledged.

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Thomas W. Kennedy

June 1977

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 Inservice 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.

Report No. 183-9, "Fatigue and Repeated-Load Elastic Characteristics of Inservice Portland Cement Concrete," by John A. Crumley and Thomas W. Kennedy, summarizes the results of an investigation of the resilient elastic and fatigue behavior of inservice concrete from pavements in Texas.

ABSTRACT

This report summarizes the results of an investigation of the resilient elastic and fatigue behavior of inservice concrete from pavements in Texas. Static indirect tensile tests were conducted in order to estimate the average tensile strength of each of the four projects tested. Repeated-load indirect tensile tests were conducted to determine the fatigue and resilient characteristics and the relationship between fatigue life and stress/strength ratio.

Deformation measurements were taken during fatigue testing in order to determine the resilient elastic properties of the material and the changes in these properties during the test period. In addition, estimates of the variation in fatigue life and elastic properties were made.

KEY WORDS: concrete, fatigue, indirect tensile test, field specimens, resilient properties, modulus of elasticity, variation.

SUMMARY

This report summarizes the findings of a study to evaluate the fatigue behavior and elastic properties of inservice portland cement concrete pavements in Texas. Changes in the elastic properties which occur with an increased number of load applications were studied, and estimates of the variation in fatigue life and elastic properties were made. In addition, attempts were made to correlate fatigue and tensile strength in order to provide a means of estimating fatigue behavior from strength results. The test methods utilized were the repeated-load and the static indirect tensile tests.

Static indirect tensile tests were also conducted in order to evaluate the effect of a capping compound which was applied to each specimen at the interface of the specimen and loading strip. The results of the static tests showed that capped specimens had higher apparent strengths and lower coefficients of variation than uncapped specimens.

The relationships between logarithm fatigue life and stress/strength ratio for the four projects tested were different although the slopes were similar. The slopes also compared favorably with those found by previous investigators. The variations in fatigue lives as indicated by the standard error of the estimate for these relationships were similar for the projects using normal-weight aggregates, ranging from 0.76 to 0.87; for the lightweight aggregate project the value was larger, 1.12.

The resilient modulus of elasticity decreased with an increase in the number of load applications. In some cases the resilient modulus of elasticity decreased by as much as 40 percent, with a significant decrease generally occuring at about 75 percent of the fatigue life. The coefficient of variation ranged from 7 to 54 percent for the resilient modulus determined at 50 percent of the fatigue life. Both the amount of the decrease and the variation of the modulus of elasticity appear to be project and material dependent.

IMPLEMENTATION STATEMENT

The results of this study to determine the fatigue and repeated-load elastic characteristics of portland cement concrete from recently constructed pavements in Texas can be used immediately in elastic layered pavement design methods currently being developed. In addition, consideration is being given to including stochastic analyses in these design methods. The results concerning the magnitude of the fatigue life and the resilient modulus of elasticity can be utilized immediately as inputs into these elastic design methods. The information on the variations of the above properties provides an estimate of the variation which occurs in actual pavements. These variation estimates are 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 fatigue properties, elastic properties, and variations of these properties as related to performance of portland cement concrete pavements.

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CHAPTER 1. INTRODUCTION

Most current pavement design methods are largely empirical and deterministic in nature. While this approach has been fairly successful, design and analysis systems based on elastic theory are currently being developed for both flexible and rigid pavements. In addition, the stochastic nature of input variables such as load, environment, and material properties can be considered.

In order to use these new techniques successfully, it is necessary to obtain information about the engineering properties of pavement materials, primarily under repeated loads. In order to afford the designer a better knowledge of expected field performance, these properties should be obtained by testing specimens from inservice pavements as well as laboratory-prepared specimens. Previous studies using the indirect tensile test have been conducted to obtain the static and repeated-load properties of inservice pavement materials (Refs 1 and 2).

Although several investigators have studied the fatigue behavior of laboratory-prepared portland cement concrete specimens, fatigue sutdies on inservice concrete are not readily available. In addition, there are areas in which more complete information is desirable, such as the changes in mechanical properties that occur when concrete is subjected to repeated loads. It would also be desirable to evaluate concrete using the indirect tensile test which has been used very successfully with other pavement materials and which is much easier to conduct than other tests.

This report summarizes the findings of a study undertaken to develop information concerning the fatigue behavior and elastic characteristics of newly constructed inservice concrete pavements in Texas and to estimate the variations that might occur in these properties. In addition, attempts were made to correlate fatigue life and tensile strength.

Chapter 2 briefly summarizes the major findings of previous investigations of the fatigue behavior and variational characteristics of portland cement concrete. 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 findings and conclusions of the study.

CHAPTER 2. CURRENT STATUS OF KNOWLEDGE

The fatigue behavior of portland cement concrete has been studied extensively during the past 75 years and a great deal of knowledge has been gained from these studies. In some instances, however, the conclusions of different investigators have been contradictory and in some cases the conclusions were not adequately supported by the data presented.

MODULUS OF ELASTICITY

All researchers who have included measurements of load and deformation for modulus of elasticity determinations have agreed that the elastic modulus decreased with increasing number of load applications (Refs 3, 4, and 5), providing the concrete undergoes no appreciable strength gain due to hydration during testing and providing the applied load is large enough to cause failure of the specimen. The changes in elastic modulus for uniaxial compression fatigue testing are illustrated schematically in Fig 1. As with elastic deformations, the permanent deformations also increase as the number of load applications increases, although they may not increase at a constant rate. When the applied load was not large enough to cause failure during the test period, the elastic and permanent deformations tended to stabilize and did not increase above this level. It is assumed, however, that if repeated loading had been continued, failure eventually would have occurred and permanent deformations would have increased.

FATIGUE

A great deal of study has been devoted to the evaluation of past fatigue studies of portland cement concrete. The results of these studies are biefly summarized below. For a more extensive summary of fatigue studies of plain concrete the reader is directed to papers by Murdock (Ref 6) and Norby (Ref 7). Summaries of early work in fatigue, including a few investigations conducted in Germany, are presented by Moore and Kommers (Ref 8), and a complete annotated bibliography of concrete fatigue studies is also availabe (Ref 9).

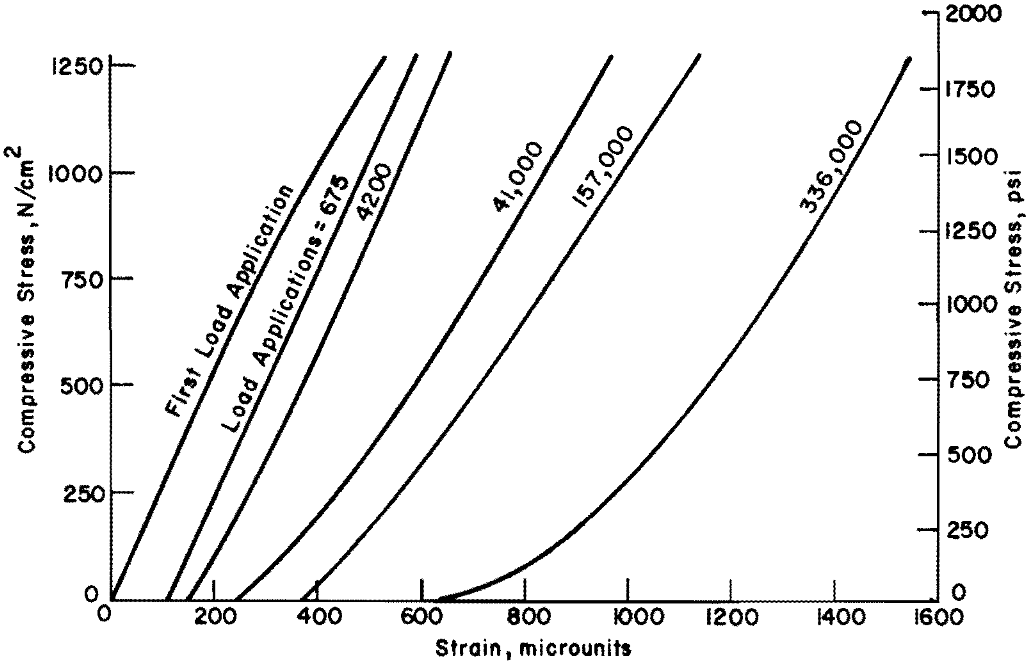


Fig 1. Stress-strain relationships for concrete compression specimens after various load repetitions (Ref 5).

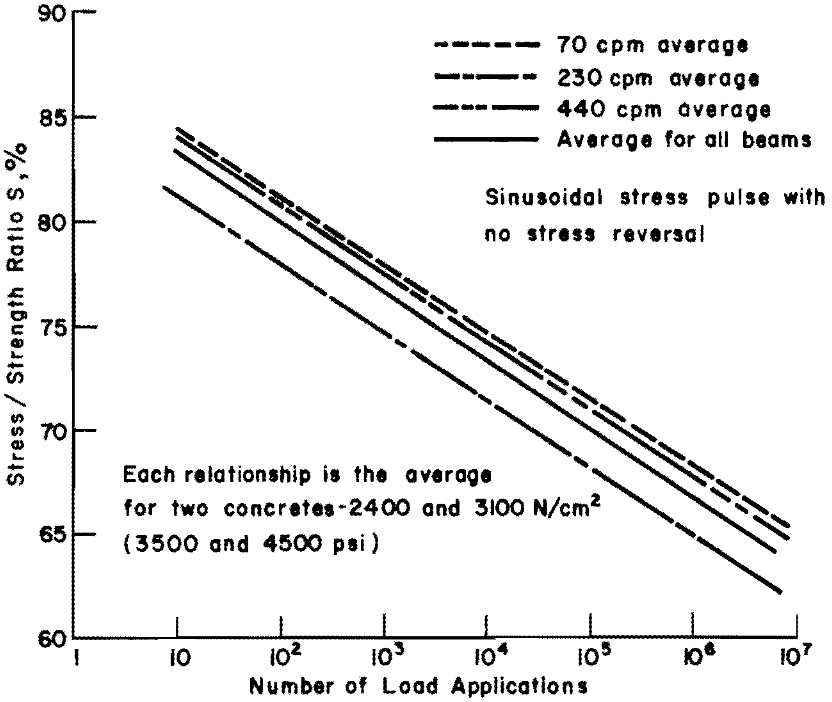


Fig 2. S-N relationships for different frequencies of loading (Ref 12).

Load Variables

The fatigue behavior of concrete seems to be independent of loading frequency for frequencies greater than about 10 cycles per minutes (Refs 10, 11, and 17). This is important since it means that fatigue tests of concrete can be conducted at high loading frequencies without significantly affecting the results. Since fatigue testing is very time consuming, any decrease in the time of testing is advantageous. The effects of loading frequency are shown in Fig 2.

Hilsdorf and Kesler (Ref 13) conducted a study of the effects of intermittent rest periods and concluded that rest periods were beneficial, i.e., the fatigue strength increased, but that no significant improvement occurred for rest periods greater than five minutes (Fig 3). Previous investigators (Refs 5 and 14) have also reported benefits from rest periods, i.e., decreased pavement deformations.

The effect of the range of applied stress has also been investigated (Refs 10 and 15), and it was shown that the fatigue life increased as the difference between the maximum and minimum applied stress decreased. The modified Goodman diagram (Fig 4) illustrates this effect and may be a useful design tool when the applied stress expected is in a given range. The diagram is entered on the vertical axis with the minimum stress, expressed as a percentage of static strength. The user proceeds horizontally to the 45° line and then vertically to the curve marked fatigue strength. The ordinate of this intersection is the maximum stress, as a percentage of the static strength, that can be allowed for a given number of load applications. This particular graph was constructed for a fatigue life of 10 million load applications, so, for the case of a minimum stress/strength ratio of 20 percent, a maximum stress equal to about 65 percent of the static strength could be applied 10 million times before failure.

Cumulative Damage

The most extensive study of cumulative damage of concrete subjected to repeated loads of different magnitude was conducted by Hilsdorf and Kesler (Ref 13). Their results indicated that the actual fatigue life depends not only on the number of load applications of given stresses but also on the sequence in which these loads are applied. They compared their experimentally obtained fatigue lives with estimated fatigue lives obtained using Miner's

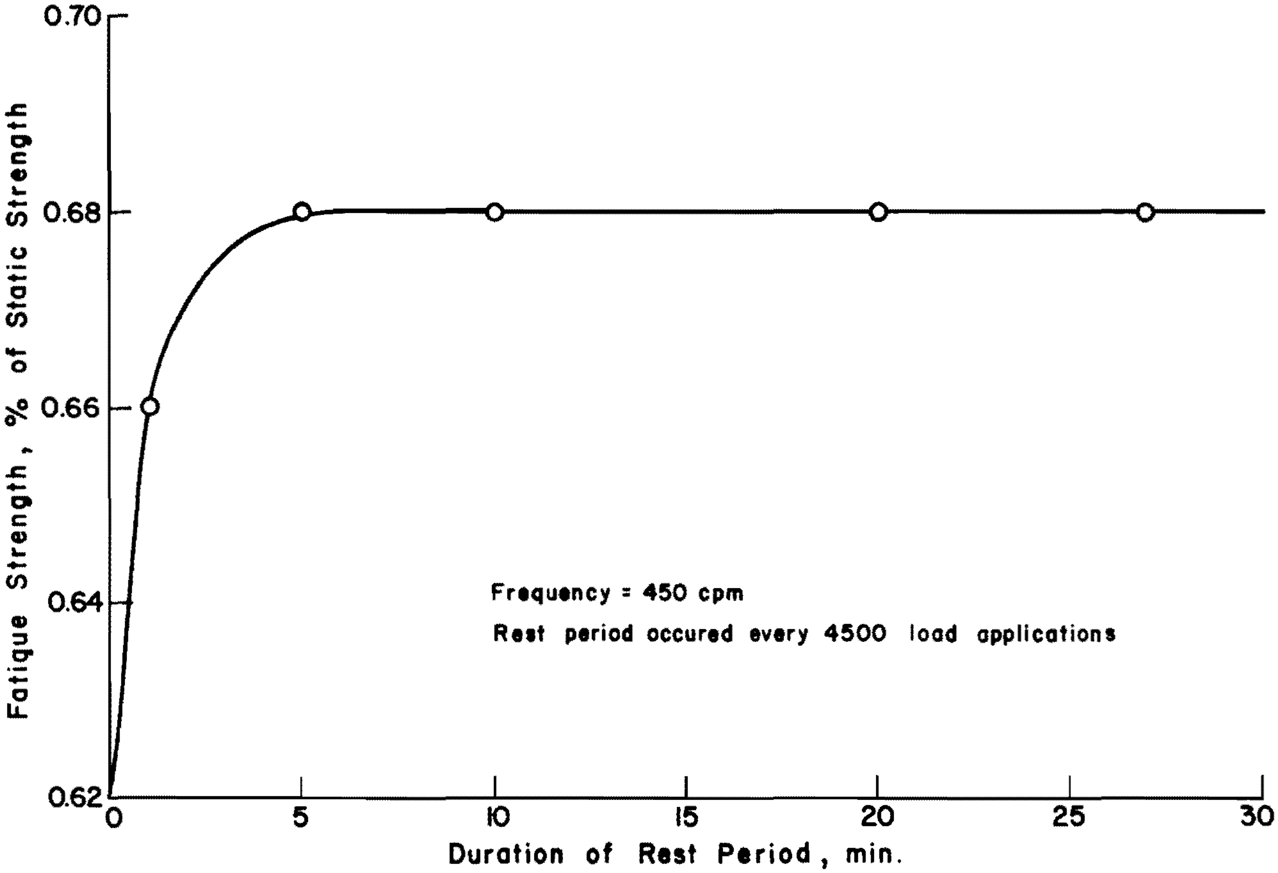


Fig 3. Effect of length of rest period on fatigue strength at ten million cycles (Ref 13).

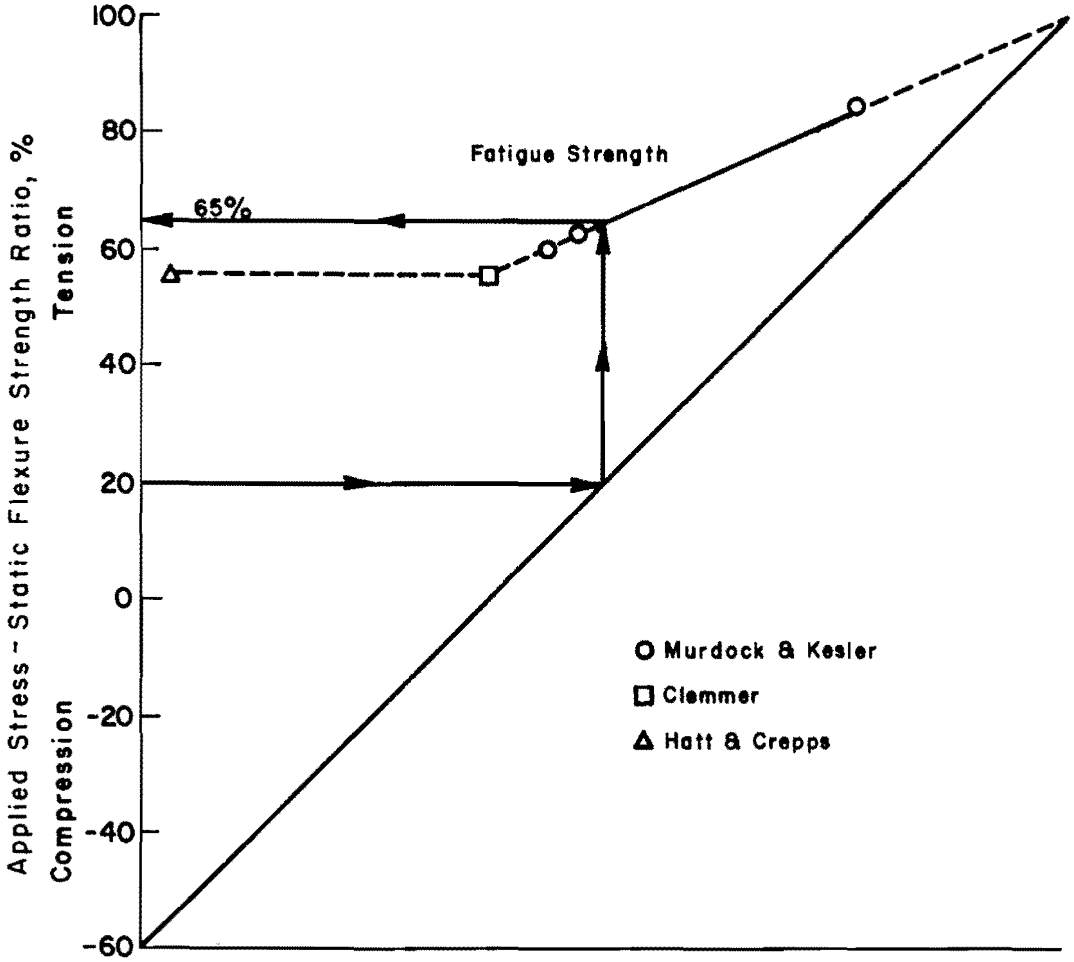


Fig 4. Modified Goodman diagram showing the effect of the range of stress on the fatigue life of plain concrete (Ref 15).

hypothesis, which assumes that each cycle in a constant stress fatigue test uses the same percentage of the fatigue life of the specimen. For stress sequences in which a specimen is subject to repeated applications of a high stress and then cycled to failure at a lower stress, Miner's hypothesis underpredicted fatigue life. For specimens subjected initially to low stresses and subsequently to higher stress levels, the predicted values exceeded the actual fatigue life.

Mixture Variables

The effect of various mixture variables has also been investigated. Among the variables considered are concrete strength (Refs 11 and 12), richness of mix (Refs 10 and 16), water-cement ratio (Ref 10), consistency of fresh concrete (Ref 15), and air entrainment (Ref 17). In all cases, when the results were expressed in terms of the relationship between the number of cycles to failure and stress/strength ratio, there was no significant difference in fatigue behavior for the variables considered.

Fatigue testing has been conducted on lightweight aggregate concrete, also. Williams (Ref 18) observed that cracks often initiated at weakened aggregate or irregularities such as air pockets. In other testing, no statistically significant difference between the fatigue behavior of lightweight aggregate concrete and normal weight concrete was detected (Ref 11).

Fatigue Failure

Most investigators have agreed that the fatigue failure of concrete is progressive in nature. However, there have been only a few experiments in which progressive failure was directly observed. Hsu et al (Ref 19) showed by direct observation of microcracking that static failure is accompanied by increased internal microcracking, and microcracks begin to grow at loads as low as 30 percent of the ultimate compressive strength. By direct observation of microcracking and by ultrasonic pulse testing, Shah and Chandra (Ref 20) observed progressive failure in creep and fatigue specimens tested at 4 to 6 cycles per minute.

There has been a good deal of disagreement concerning the existence of a fatigue limit for concrete. Generally, early investigators, prior to about 1940, supported the contention that concrete had a fatigue limit while later investigators did not. It can be argued that the earlier investigators did not subject the specimen to enough load applications to produce failure and that the latter did not test at low enough stress levels to find a possible fatigue limit. Thus, no definite conclusion can be made.

VARIATIONAL CHARACTERISTICS

There are several properties of highway pavement materials which are of interest. Among these are strength, modulus of elasticity, and Poisson's ratio, for both static and fatigue loadings. Pavement thickness and density are also of interest. It has been recognized that each of these properties will have a certain amount of variation associated with it. The variation observed when measuring any of these properties σ_o will be a function of inherent material variation σ_m, variation due to testing σ_t, and sampling variation σ_s :

$$\sigma_o^2 = \sigma_m^2 + \sigma_t^2 + \sigma_s^2$$

Material variation is due to differences in raw material, production, and construction, whereas testing and sampling variations result from the measurement process. Clearly, it is desirable to use sampling and testing procedures that yield the least variation.

Studies of the properties of as-placed concrete can be separated into two categories, those which used test specimens cast at the job site and those which used specimens sawed or cored from the hardened concrete pavement. It has been shown by Walker and Bloem (Ref 21) that concrete beams obtained by sawing may give lower strengths and higher coefficients of variation than beams molded from the same batch. In their test procedure, 76 × 102 × 406-mm (3 × 4 × 16-in.) and 152 × 152 × 914-mm (6 × 6 × 36-in.) beams were cast from the same concrete batch. Each of the larger beams was sawed to make four smaller beams for testing. The beams were tested using the third point loading method. The strengths of the sawed beams were about 25 percent lower than the strengths of the molded beams and there was an increase in variance which could influence a comparison of results from different investigations.

According to Abdun-Nur (Ref 22), the U. S. Bureau of Reclamation has consistently obtained a coefficient of variation of 15 percent for the strength of concretes used in their projects. Since the Bureau exercises a high degree of quality control, this level of variance might be expected for concrete of above average quality. Abdun-Nur observed coefficients of variation for many jobs to be from 18 percent to 25 percent. He considered a value of 20 percent to be reasonable for average quality concrete.

At the AASHO Road Test (Ref 23), a fairly extensive investigation of concrete quality was conducted. Two beams and two cylinders were molded from two randomly selected batches for each 37-m (120-ft) structural section. For the 73-m (240-ft) structural sections, four beams and four cylinders were made from four separate batches. The results of the strength tests at 14 days are shown in Table 1. Considering the amount of care exercised in all facets of the AASHO Road Test, these variances could be taken as lower limits and greater variance would be expected under normal field conditions. It should also be pointed out that each compression test result was the average of two specimens and each flexure test result was the average of two breaks of one beam, a procedure which will produce smaller variance values than if each break is treated as a separate test.

Data from five projects in West Virginia (Ref 24) on the variation of the 28-day compressive strength of paving concretes indicated a range of variation from 9.8 to 16.5 percent (Table A1, Appendix A).

The State Department of Highways of Colorado (Ref 25) conducted an extensive investigation of the effects of vibration on concrete pavements. In this study, specimens were cored from the hardened concrete for compression tests. The cores were sawed in half to provide specimens with diameters of 51 mm (2 in.) and heights of 102 mm (4 in.). This allowed the investigators to determine if there were significant differences in the strengths of the upper and lower portions of the roadway. The overall average coefficient of variation was about 23 percent for one project and 12 percent for the other (Table A2, Appendix A). The data also show that the bottom cores had a higher average strength than the top cores for both projects.

Narrow and Ullberg (Ref 26) conducted a study of the indirect tensile test and its applications to airfield pavements. In the field analysis portion of the study, specimens with diameters of 152 mm (6 in.) and heights of 305 mm (12 in.) were cored from existing pavements. The test procedure consisted of loading the specimens through loading strips which were 51 mm (2 in.) wide and 3.2 mm (1/8 in.) thick. The coefficient of variation for the different projects ranged from 4 to 19 percent, with an average value of 12.3 percent.

TABLE 1. SUMMARY OF RESULTS FROM TESTING OF CONCRETE FROM AASHO ROAD TEST (Ref 23)

Loop	Flexural Strength,[1] 14 days						Compressive Strength,[2] 14 days					
	No. Tests	Mean, N/cm^2	(psi)	Std. Dev., N/cm^2	(psi)	Coef. Var., %	No. Tests	Mean, N/cm^2	(psi)	Std. Dev., N/cm^2	(psi)	Coef. Var., %
	64 mm (2½ in.) Maximum Size Aggregate											
1	16	439	(637)	32	(46)	7.2	8	2481	(3599)	200	(290)	8.1
2	20	447	(648)	26	(37)	5.7	9	2484	(3603)	194	(281)	7.8
3	71	434	(630)	30	(44)	7.0	38	2567	(3723)	208	(301)	8.1
4	96	449	(651)	26	(38)	5.8	48	2801	(4062)	198	(288)	7.1
5	96	434	(629)	19	(28)	4.4	48	2893	(4196)	268	(388)	9.2
6	99	433	(628)	35	(51)	8.1	48	2732	(3963)	224	(325)	8.2
All	398	438	(636)	31	(45)	7.1	199	2734	(3966)	259	(376)	9.5
	38 mm (1½ in.) Maximum Size Aggregate											
1	4	466	(676)	45	(65)	9.6	2	2819	(4088)	112	(162)	4.0
2	39	461	(668)	30	(44)	6.6	19	2790	(4046)	203	(295)	7.3
3	24	460	(667)	32	(47)	7.0	14	2712	(3933)	303	(440)	11.2
All	67	461	(668)	32	(46)	6.9	35	2761	(4004)	243	(352)	8.8

[1] Average of two breaks on one beam.

[2] Average of two specimens.

In previous research at The University of Texas at Austin (Ref 1), concrete specimens were cored from ten projects in six districts of the State Department of Highways and Public Transportation. Each 102-mm (4-in.) diameter core was cut into three 51-mm (2-in.) high specimens and tested using the indirect tensile test. The average indirect tensile strengths and static moduli of elasticity of the top, center, and bottom specimens are shown in Table 2. The coefficients of variation for the tensile strengths of the various projects were consistently near 20 percent. The variance of the modulus of elasticity ranged from 22 percent to 44 percent. When the results are analyzed taking into account the position of the specimen in the core, it is apparent that the bottom specimens were stronger than the top or center specimens (Table 3). In addition, most of the coefficients of variation were less than 20 percent. The bottom specimens also tended to be stiffer than the top or center specimens.

SUMMARY

Repeated load testing has been conducted on portland cement concrete for many years and a great deal of information has been gained. However, some of the conclusions have not yet been corroborated and some conclusions are contradictory. In addition, all studies for which information is readily available have involved only laboratory-prepared specimens.

Several agencies have investigated the variation of properties of as-placed concrete. Generally the concrete strength had a coefficient of variation in the range of 10 to 25 percent, depending on the quality of the concrete and the care exercised during construction. Variation in the modulus of elasticity has not been investigated nearly as extensively as strength. The only available data indicate that the coefficient of variation for the modulus of elasticity of field cores is in the range of 20 to 40 percent.

The development of pavement design methods has progressed to the point that fatigue properties, elastic properties, and variability of material properties can be incorporated in the design process. In order to use these methods effectively, the designer needs reliable values for these properties. However, there is currently no information available concerning the fatigue behavior of inservice concrete and there is only limited information concerning elastic properties of concrete under repeated load and variation of pavement material properties in Texas.

TABLE 2. SUMMARY OF AVERAGE TEST RESULTS FOR EACH SPECIMEN[1] (Ref 1)

District Project Identification	Aggregate Type	Number of Specimens	Distance Covered,		Tensile Strength			Modulus of Elasticity[2]			Density		
					Mean,		Coef. Var., %	Mean,		Coef. Var., %	Mean,		Coef. Var., %
			km	mi	N/cm^2	psi		N/cm^2	psi		Kg/m^3	pcf	
2A	Limestone	104	27.4	17.0	316	459	19	2.85	4.14	40	2252	140.6	1.1
2E	Limestone	134	44.0	27.3	338	490	20	2.55	3.70	35	2244	140.1	1.6
12Sp	Gravel	46	—	—	321	466	29	2.52	3.66	36	2219	138.5	4.7
13Sp	Gravel	28	—	—	403	584	19	3.02	4.38	22	2254	140.7	1.7
17B	Gravel	141	37.5	23.3	343	498	19	3.46	5.02	26	2281	142.4	2.0
17M	Gravel	122	35.4	22.0	295	428	20	2.50	3.62	37	2263	141.3	1.4
18N	Limestone	25	7.4	4.6	292	424	19	2.58	3.74	24	2275	142.0	1.8
18O	Limestone	72	6.8	4.2	390	566	19	2.92	4.24	26	2342	146.2	1.2
19A	Gravel	72	25.9	16.1	294	427	21	2.32	3.36	42	2257	140.9	1.5
19B	Iron Ore Slag, Gravel	63	20.8	12.9	270	391	20	2.34	3.40	42	2132	133.1	1.9
		Weighted Average			325	471	20	2.75	3.99	34	—	—	1.7
		Range			133	193	10	1.14	1.66	20	—	—	3.6
		Coef. Var. of Means, (%)			—	—	13	—	—	13	—	—	—

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

[2] Assumed Poisson's ratio = 0.20.

TABLE 3. TENSILE STRENGTH AND MODULUS OF TOP, CENTER, AND BOTTOM SPECIMENS FROM CONCRETE CORES (Ref 1)

District Project Identification	Tensile Strength, N/cm^2 (psi)						Modulus of Elasticity, 10^6 N/cm^2 (10^6 psi)					
	Top		Center		Bottom		Top		Center		Bottom	
	Mean	Coef. Var., %	Mean	Coef. Var., %	Mean	Coef. Var., %	Mean	Coef. Var., %	Mean	Coef. Var., %	Mean	Coef. Var., %
2A	302 (438)	18	312 (453)	17	334 (484)	19	2.84 (4.12)	46	2.61 (3.78)	28	3.09 (4.48)	40
2E	321 (466)	19	320 (464)	20	369 (535)	17	2.61 (3.78)	43	2.50 (3.62)	23	2.55 (3.70)	33
17B	314 (455)	19	329 (477)	19	384 (557)	15	3.22 (4.67)	31	3.41 (4.95)	27	3.72 (5.39)	21
17M	274 (397)	18	298 (432)	16	314 (455)	21	2.30 (3.33)	39	2.38 (3.45)	43	2.80 (4.06)	28
19A	278 (403)	23	308 (446)	20	303 (440)	20	2.25 (3.27)	47	2.46 (3.57)	47	2.31 (3.35)	36
19B	269 (390)	16	258 (374)	16	274 (398)	25	2.39 (3.47)	42	2.04 (2.96)	25	2.39 (3.47)	45

Note: Based on Table 3 of Ref 1; coefficients of variation have been added for the top, center, and bottom specimens.

CHAPTER 3. EXPERIMENTAL PROGRAM

The primary objective of this investigation was to characterize the behavior of inservice portland cement concrete from pavements when subjected to repeated-load testing, which can be subdivided as follows:

(1) to determine modulus of elasticity, Poisson's ratio, and fatigue life of inservice concrete under repeated loads,

(2) to estimate the variation in these properties,

(3) to determine the changes in the elastic properties due to repeated loads, and

(4) to investigate possible correlations between static behavior and repeated-load behavior.

Cores are routinely taken from newly completed pavements by the Texas State Department of Highways and Public Transportation in order to determine pavement thickness. A large number of these cores were obtained for determining concrete properties under both static and repeated loading using the indirect tensile test. This test was used because of its previous use in evaluating pavement materials, the fact that it can be used to evaluate all cohesive materials, the ease with which it can be conducted, and the fact that it can be used to obtain all properties required for elastic analysis. Previously obtained static test results are summarized in Ref 1.

DESCRIPTION OF PROJECTS

Specimens from four projects located in three districts were tested. Summary information related to the projects is shown in Table 4. Figure 5 shows the geographic distribution of the districts from which the cores were obtained.

The cores were generally taken from the pavements every 305 m (1,000 ft) by systematic random sampling. The cores used in the fatigue study were randomly chosen from the cores not used in the static tests. Because of the time involved in fatigue testing, only four paving projects were included in the testing program.

TABLE 4. SUMMARY OF PROJECTS TESTED

District Project Identification	Aggregate Type	Cement Factor, sacks/yd^3	Water-Cement Ratio		Beam Strength*	
			by weight	gal./sack	N/cm^2	psi
2E	Limestone	4.3	0.58	6.5	448	650
17B	Gravel	4.5	0.59	6.7	396	575
17M	Gravel	4.5	0.59	6.7	396	575
19B	Iron ore, slag, gravel	5.0 to 5.9	0.43 to 0.53	4.9 to 6.0	396	575

*Seven-day field curing, center point loading, using cast beams.

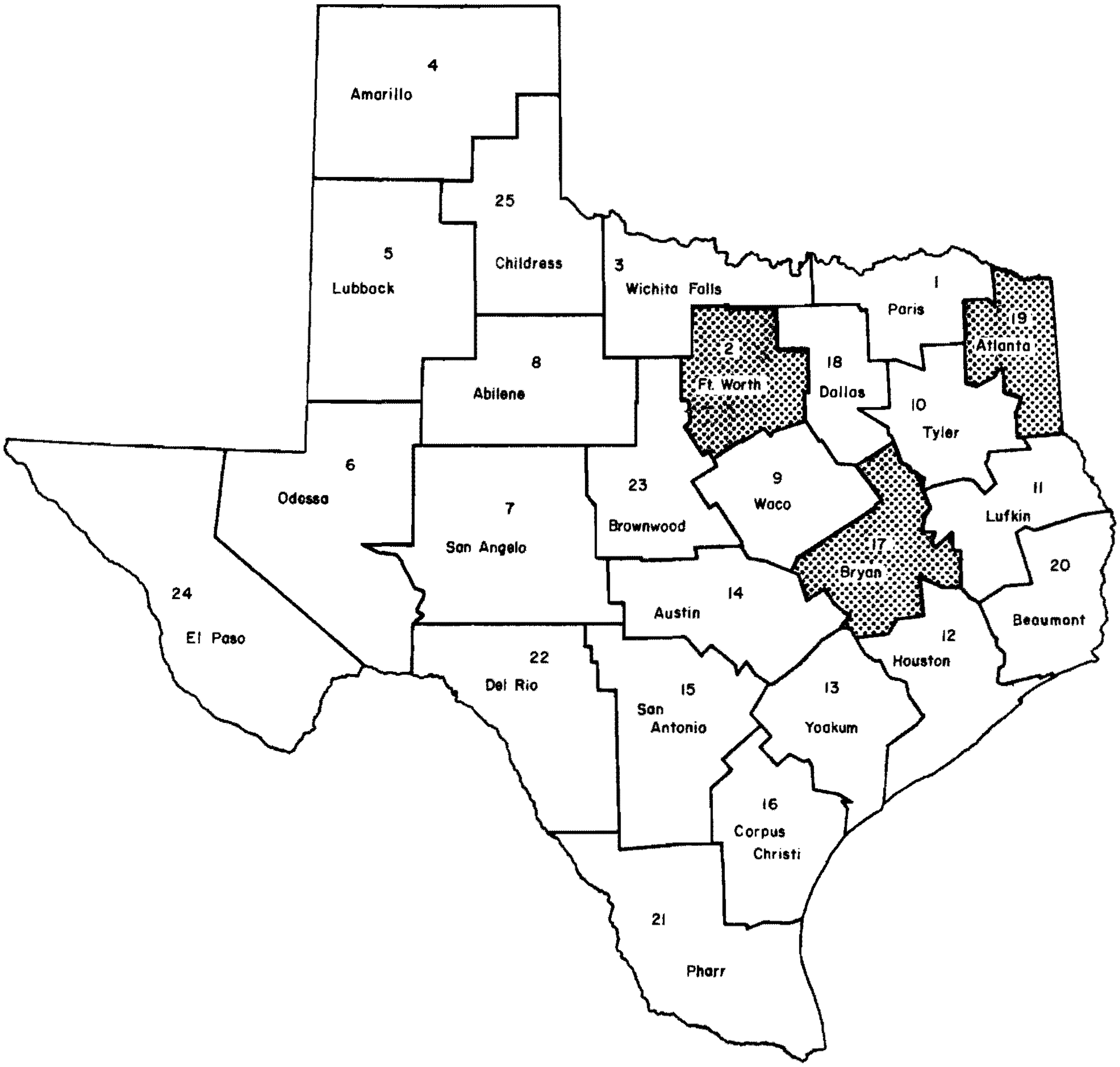


Fig 5. Districts from which specimens were obtained and tested.

SPECIMEN PREPARATION

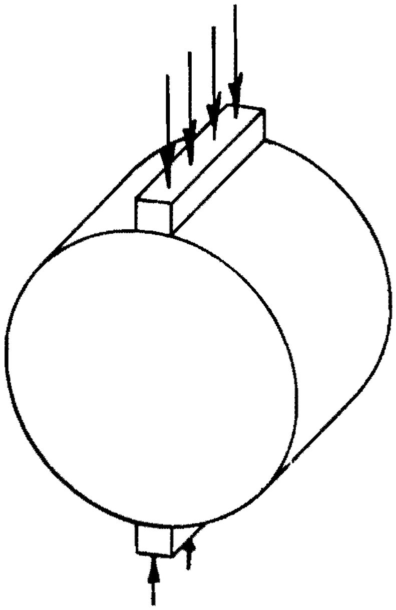
All cores had a diameter of approximately 102 mm (4 in.). The specimens, which were cut from the cores, had heights of 51 mm (2 in.). In the previous study of static properties (Ref 1), the specimens were tested with no further preparation. For this study, it was felt that the surface of the cores was too irregular for the applied load to be distributed uniformly. An attempt was made to machine the surface smooth, but this proved uneconomical. Therefore, a capping compound, a high strength gypsum plaster, was applied to smooth the irregularities. The capping compound was applied as thin as possible so as to minimize its effects on the recorded vertical deformation of the specimens. The apparatus used in the capping produced a radius of curvature of 51 mm (2 in.) for the surface of the cap, which was the same as the radius of the specimens.

For this study, all specimens were from the lower portion of the core, since it represents the portion of the pavement subjected to the highest load-induced tensile stress. However, a previous study (Ref 1) found that strength and modulus of elasticity tend to increase with depth in the pavement.

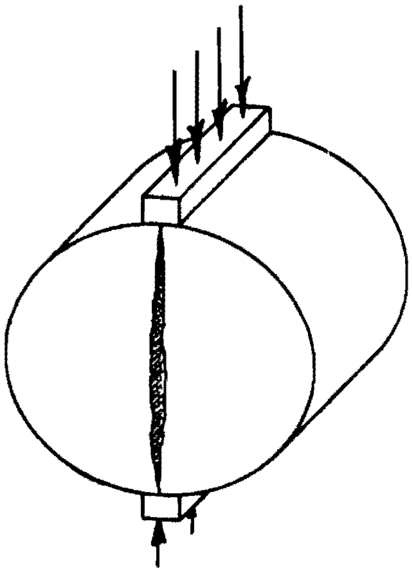
INDIRECT TENSILE TEST

All testing was done using the indirect tensile test, which has been used for the evaluation of other materials in related studies. The indirect tensile test consists of loading a cylindrical specimen with compressive loads acting parallel to and along the vertical diametral plane, as shown in Fig 6. The load is distributed through 13-mm (0.5-in.) wide steel loading strips which are curved at the interface with the specimen. The curved surface had a radius of 51 mm (2 in.).

When the load is applied, compressive stresses are induced parallel to and along the vertical axis, as shown in Fig 7. The stresses perpendicular to and along the vertical axis are fairly uniform tensile stresses over approximately the center 70 percent of the specimen. Failure generally occurs by splitting along the vertical axis (Fig 6b). Estimates of the modulus of elasticity and Poisson's ratio can be obtained using the applied load and corresponding vertical and horizontal deformations (Refs 28 and 29). In this case, only the resilient horizontal deformation H_{RI} was measured and a value for Poisson's ratio was assumed.



(a) Compressive load being applied.



(b) Specimen failing in tension.

Fig 6. Indirect tensile test loading and failure.

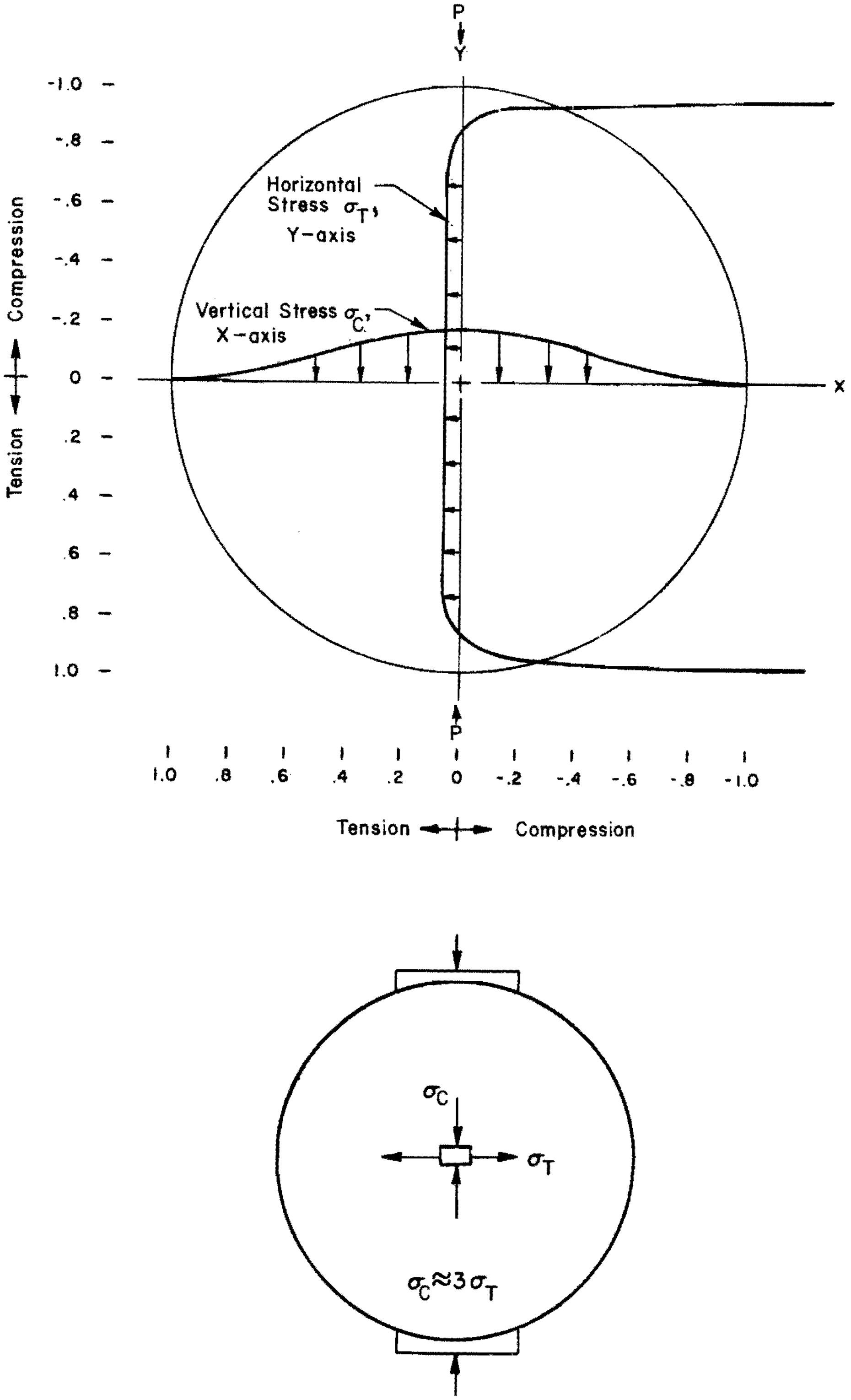


Fig 7. Relative stress distributions and center element showing biaxial state of stress for the indirect tensile test.

Test Equipment

The test equipment was basically the same as that used in previous studies conducted at the Center for Highway Research and included a loading frame, a loading head, and an MTS electrohydraulic loading system. The loading head was a modified commercially available die set with the lower and upper platens constrained so that the platens always remain parallel.

In the static tests vertical deformations were measured by a DC linear variable differential transducer (LVDT) positioned on the upper platen, centered as closely as possible, above the specimen. Loads were measured using a load cell. The loads and corresponding vertical deformations were recorded on an X-Y plotter.

In the repeated-load tests, loads and vertical deformations were not measured. Loads were preset to produce the desired stress level and were verified at the end of the test. Horizontal deformations H_{RI} were measured at 25, 50, and 100 cycles and then were periodically monitored during the remainder of the test. Horizontal deformations were measured by means of two LVDT's, positioned on opposite sides of the specimen and in direct contact with the specimen, and were recorded on an X-Y plotter.

Static Test Procedure

Since fatigue specimens were to be capped, capped specimens were prepared for the static tests, also. The static test procedure was essentially the same as that used previously (Ref 1). 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. The specimen was then loaded at a rate of 13 mm (0.5 in.) per minute. Loads and vertical deformation were continuously recorded on an X-Y plotter.

Repeated-Load Test Procedure

A seating load of 89 N (20 lb), which corresponds to a tensile stress of about 1.1 N/cm^2 (1.5 psi), was also used in these tests and was maintained as the minimun load throughout the test. The purpose of the preload was to prevent impact loading and to reduce movement of the specimen. Then repeated total loads producing total tensile stresses ranging from 217 to 356 N/cm^2 (315 to 516 psi) were applied in the form of a haversine 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, which was considered to occur when the specimen fractured completely, or until a minimum of 500,000 load applications had been applied with very little increase in deformation. A typical load pulse and a trace of the corresponding horizontal deformation are shown in Fig 8.

PARAMETERS INVESTIGATED

The parameters analyzed in this study were indirect tensile strength S_T, resilient modulus of elasticity E_{IR}, and fatigue life N_f. Fatigue life is the number of load applications required to completely fracture the specimen.

Values of S_T and E_{IR} were calculated using a computer program, MODLAS 9. A Poisson's ratio of 0.20 was assumed for the calculation of the modulus value. If the computer program is not used, values of S_T and E_{IR} can be calculated for 102-mm (4-in.) diameter specimens using the following equations:

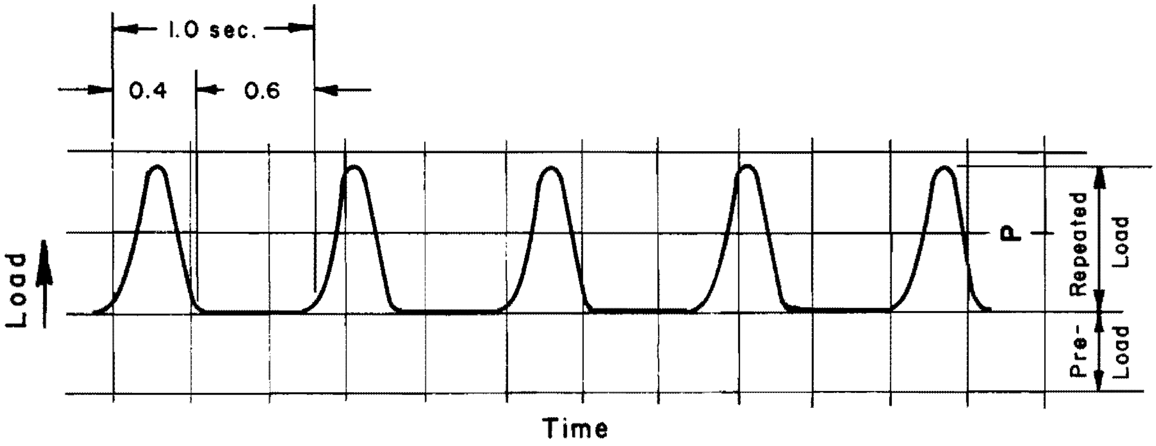
$$S_T = \frac{0.156\, P_{Fail}}{h}$$

$$E_{IR} = \frac{P}{H_{RI} h}(0.269 + 0.997\nu)$$

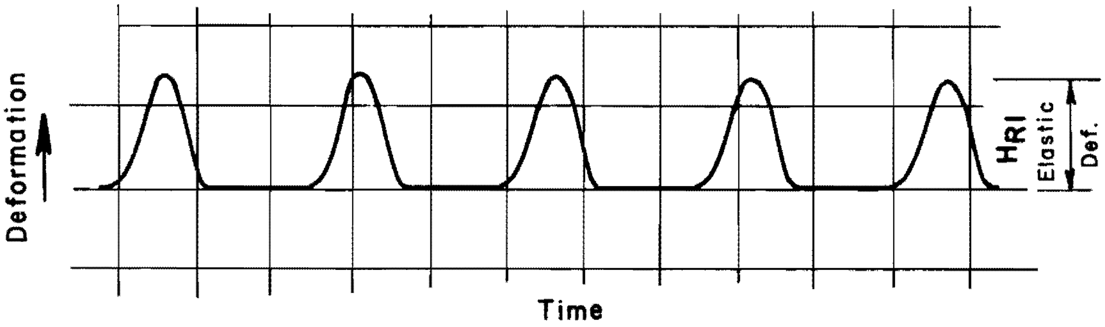
where

P_{Fail} = total load at failure, pounds,
P = repeated load, pounds,
h = height of specimen, inches,
H_{RI} = instantaneous resilient horizontal deformation, inches, and
ν = Poisson's ratio.

For other diameters, the constants will be different (Ref 29).



(a) Load pulse.



(b) Horizontal deformation.

Fig 8. Load pulse and corresponding horizontal deformations.

CHAPTER 4. ANALYSIS AND EVALUATION OF TEST RESULTS

The primary objective of this study was to determine the fatigue and elastic properties of inservice portland cement concrete and to estimate the variation of these properties for use in the design of pavements. The findings of this study are presented in two main sections. The first deals with the relationships between stress/strength ratio and fatigue life and includes a comparison with the results of other investigators. The second section deals with the elastic modulus of concrete under fatigue loading and the changes in modulus that might be expected to occur during the life of the material.

TENSILE STRENGTH

In order to analyze the fatigue results, it was necessary to obtain some estimate of the indirect tensile strength of the concrete. All specimens used in this study were capped to minimize surface irregularities. Since the specimens used in the previous study of static properties (Ref 1) were not capped, separate static tests were conducted to determine the effects of the capping process.

As shown in Table 5, the strength of the capped specimens was approximately 30 percent greater than the strength of the uncapped specimens. The range of tensile strength for the uncapped specimens was 274 to 384 N/cm^2 (398 to 557 psi) while for the capped specimens the range was 362 to 491 N/cm^2 (525 to 712 psi).

A comparison of the coefficients of variation of the capped and uncapped specimens indicates that generally the coefficients were much less for the capped specimens than for the uncapped specimens, indicating that a large portion of the previously measured variation (Ref 1) was due to error introduced by surface irregularities of the specimens. For capped specimens the coefficients ranged from 8 to 16 percent.

TABLE 5. SUMMARY OF INDIRECT TENSILE STRENGTHS FOR UNCAPPED AND CAPPED SPECIMENS

District Project Identification	Uncapped Specimens (Ref 1)				Capped Specimens			
	Number of Specimens	Mean		Coef. Var., %	Number of Specimens	Mean		Coef. Var., %
		N/cm^2	psi			N/cm^2	psi	
2E	48	369	535	19	15	433	628	8
17B	49	384	557	15	10	491	712	16
17M	42	314	455	21	14	439	636	9
19B	27	274	398	25	15	362	525	12

FATIGUE LIFE

Traditionally, the results from fatigue tests of concrete have been expressed in terms of an S-N curve, i.e., the relationship between the logarithm of the number of load applications to failure and either applied stress or stress/strength ratio. Most investigators have preferred to base their results on the stress/strength ratio since this approach has provided a better comparison of the fatigue behaviors of different strength concretes.

It is generally accepted that there is a linear relationship between the logarithm of fatigue life and stress/strength ratio over a range of stress/strength ratios from about 55 to 85 percent of the static strength. The stress/strength ratios were calculated on the basis of the tensile strengths summarized in Table 5.

This linear relationship generally is expressed as

$$\log N_f = C_1 S + C_2$$

where

N_f = fatigue life,
S = stress/strength ratio, percent,
C_1 = slope of the semilogarithmic relationship, and
C_2 = intercept of the semilogarithmic relationship.

The method of least squares was used to establish the line of best fit and to evaluate the two constants, C_1 and C_2. Results of tests which were terminated before failure due to very large load repetitions were included in the regression analysis since it was felt that including them would produce a more accurate characterization of the fatigue behavior.

Fatigue Life Relationships

The first series of tests, Project 2E, involved subjecting specimens to repeated loads at several stress levels in order to evaluate the linearity of the relationship between the logarithm of fatigue life and stress/strength ratio. The resulting S-N relationship is shown in Fig 9, which indicates a linear relationship with an R^2 value of 0.59. Since nearly all of the

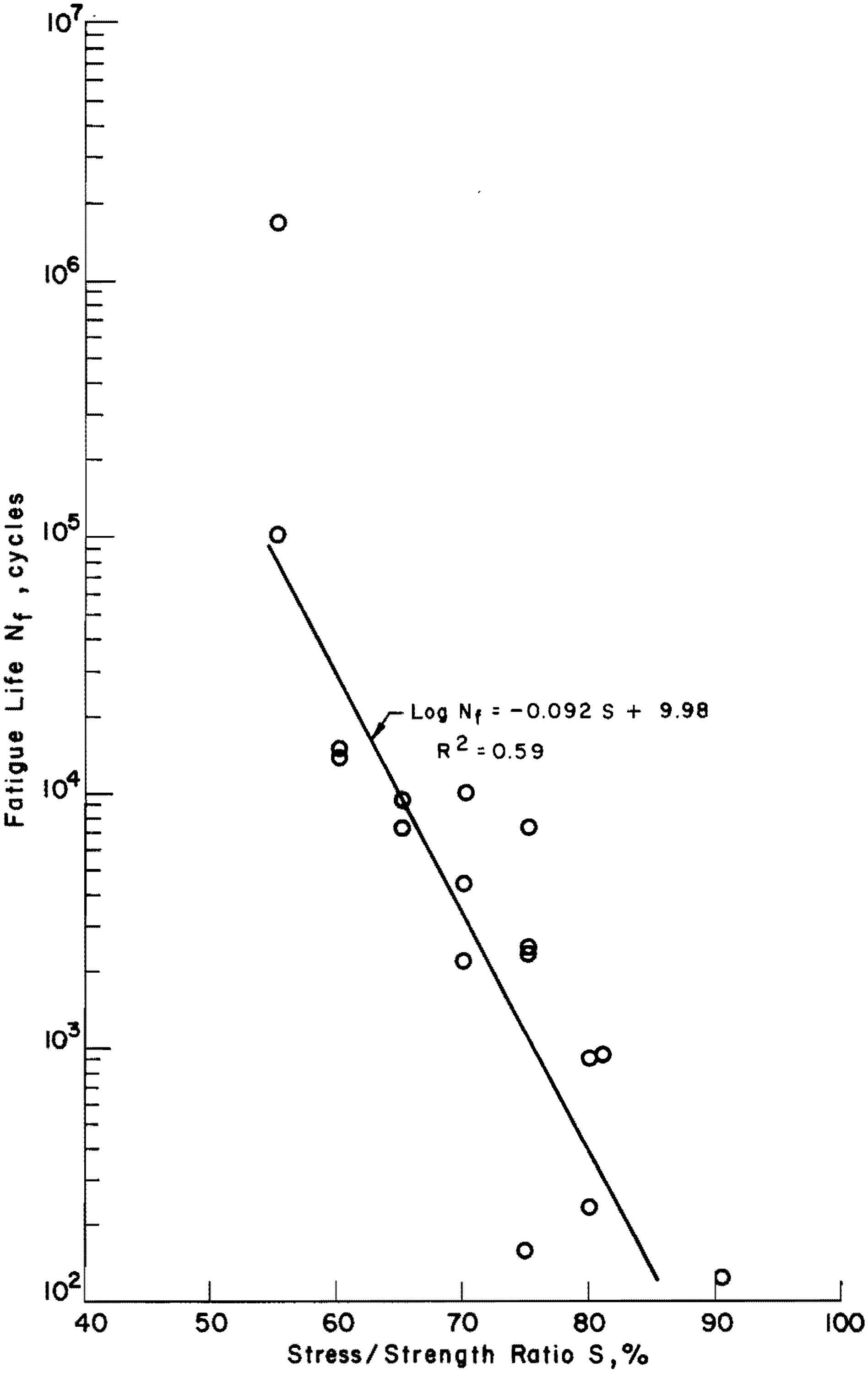


Fig 9. Typical S-N relationship for inservice concrete - Project 2E.

previous investigators had agreed that the relationship is linear, only two stress levels were used for the three remaining test series. The S-N curves and the actual data points for Projects 17B, 17M, and 19B are shown in Appendix B.

It would be useful to have relationships between strength and fatigue behavior since this would make it feasible to use the results of the much simpler, faster static tests in order to estimate fatigue life.

For comparison purposes, the S-N curves for all four projects, which differed in strength by 35 percent, are shown in Fig 10. The slopes of all four lines are approximately equal; however, the curves are displaced vertically. Previous studies have shown that the fatigue behaviors of the concretes tested are similar when the results are expressed in terms of stress/strength ratio. Thus, in this study, the change in fatigue life produced by a change in stress was approximately the same, although the fatigue lives differed.

With respect to the displacement, or difference in fatigue lives, Fig 10 indicates that an error in estimating strength of only 5 percent would result in a significant displacement of the curves but would not necessarily change the slopes. Since the number of specimens tested was relatively small, the estimates of static strength could easily have been in error. Using Project 17M as an example, the 95 percent confidence interval for the mean is 439 ± 79 N/cm^2 (636 ± 114 psi). In other words, there is a 95 percent probability that the mean strength of the concrete of Project 17M is between 360 and 518 N/cm^2 (522 and 780 psi). Thus, a 5 percent strength difference, 15 N/cm^2 (22 psi), could easily occur.

The results presented indicate that different concretes did not exhibit similar fatigue behaviors, even when the results were expressed in terms of stress/strength ratio. However, the results are not conclusive, and further investigation is needed before a definite conclusion can be made.

A summary of results of three fatigue studies on laboratory-prepared specimens is shown in Table 6. In some cases, the values in the table were not reported in the original paper and had to be calculated from the data presented in the S-N curves. The S-N curves derived from Table 6 are shown in Fig 11, together with the results of this study.

As shown by the S-N curves (Fig 11), the fatigue lives for the cores tested in this study were less than the fatigue lives of the laboratory specimens and the variations were larger, as expected. It is apparent that the

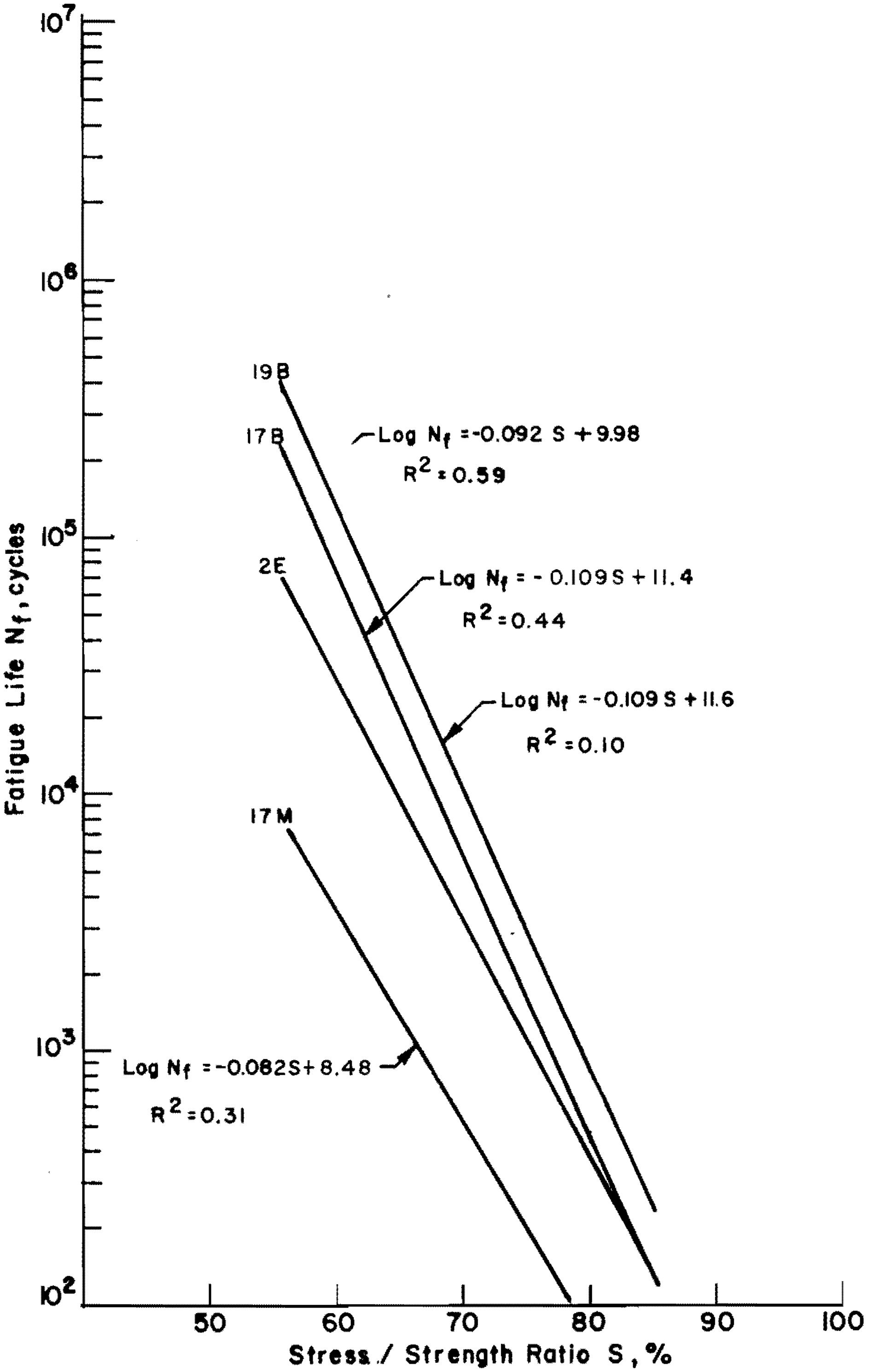


Fig 10. S-N relationships for all projects.

TABLE 6. SUMMARY OF RESULTS FROM PREVIOUS FATIGUE INVESTIGATIONS

Investigation	C_1	C_2	Coefficient of Determination R^2	Standard Error of Estimate	Test Method
Kesler (Ref 12)					
70 cpm, 3600-psi concrete	-0.203*	19.22*	0.55*	1.32*	Flexure
70 cpm, 4600-psi concrete	-0.186*	17.81*	0.55*	1.20*	Flexure
Antrim and McLaughlin (Ref 17) non-air-entrained concrete	-0.106	12.26	0.88	0.75*	Compression
air-entrained concrete	-0.214	20.50	0.38	0.47*	Compression
Williams (Ref 18)	-0.0426*	6.87*	0.27*	0.61*	Flexure**

*These values were calculated from points obtained from reported S-N curves and are, therefore, subject to inaccuracies in reading the curves.

**The method used by Williams was not a standard test. The original paper should be consulted for details.

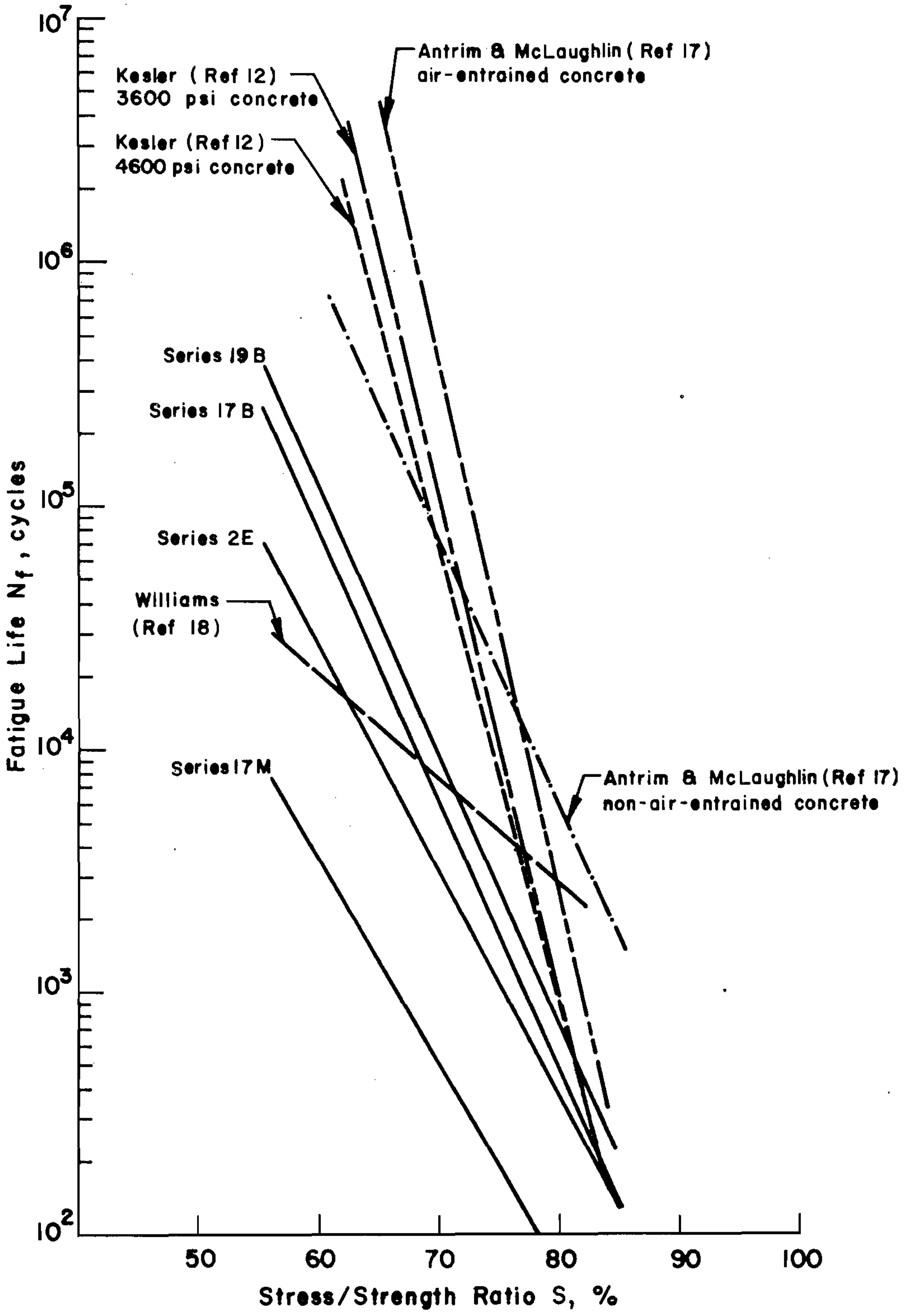


Fig 11. Comparison of relationships between fatigue life and stress/strength ratio.

differences in the slopes of the curves are relatively small, which is significant, considering that different test methods were used to evaluate different mixture designs and materials. However, the relationships are displaced as previously observed.

Variation of Fatigue Life

The individual S-N relationships (Appendix B) indicate that there is a great deal of variation associated with fatigue testing. The coefficients of variation for each stress level of the projects tested are given in Table 7. Since the distribution of fatigue life is generally log-normal, these coefficients of variation were based on the logarithm of fatigue life.

Of more significance is the standard error of the estimate S_e given in Table 8. The standard error of the estimate directly expresses the degree of scatter in the data. A large value for S_e indicates higher scatter. For Projects 2E, 17B, and 17M, the values of S_e are very similar, which indicates that the scatter of the test results is about the same. However, Project 19B exhibits a much larger degree of variation than the other projects. As shown in Table 4, the mixture in 19B contained iron ore slag and a larger range of cement factors and water/cement ratios.

ELASTIC CHARACTERISTICS UNDER REPEATED LOADING

It has been shown previously that the modulus of elasticity of concrete changes during fatigue testing. One objective of this study was to determine how the modulus changed with increasing load repetitions. The moduli of elasticity evaluated in this study were calculated from horizontal deformation measurements and an assumed value for Poisson's ratio of 0.20. Graphical presentations of the change in modulus for increasing load repetitions are shown in Figs 12 through 16, which show calculated elastic modulus versus the number of load applications expressed as a percent of fatigue life.

The results for Project 2E (Figs 12 and 13) show a more well-defined trend in behavior than the other projects. Almost all the specimens exhibited a slight decrease in elastic modulus in the interval between about 10 and 75 percent of the fatigue life. At approximately 75 percent of the fatigue life, the measured deformations began to increase more rapidly, thereby causing a decrease in elastic moduli. Although not shown in the figures, the deformations often increased markedly with each load repetition when the specimen

TABLE 7. COEFFICIENT OF VARIATION OF FATIGUE RESULTS

District Project Identification	Stress-Strength Ratio, %	Number of Specimens	Fatigue Life Predicted by Regression Equation, cycles	Coefficient of Variation, %
2E	75.0	4	1,108	24
17B	72.5	5	3,010	21
	60.0	5	70,150	20
17M	72.5	4	333	27
	60.0	5	3,548	28
19B	68.0	5	16,780	16
	62.0	5	75,540	38

TABLE 8. SUMMARY OF FATIGUE TEST RESULTS

District Project Identification	Linear Regression Values			
	C_1	C_2	Coefficient of Determination R^2	Standard Error of the Estimate
2E	-0.0924	9.98	0.59	0.76
17B	-0.109	11.40	0.44	0.87
17M	-0.0822	8.48	0.31	0.86
19B	-0.109	11.63	0.10	1.12

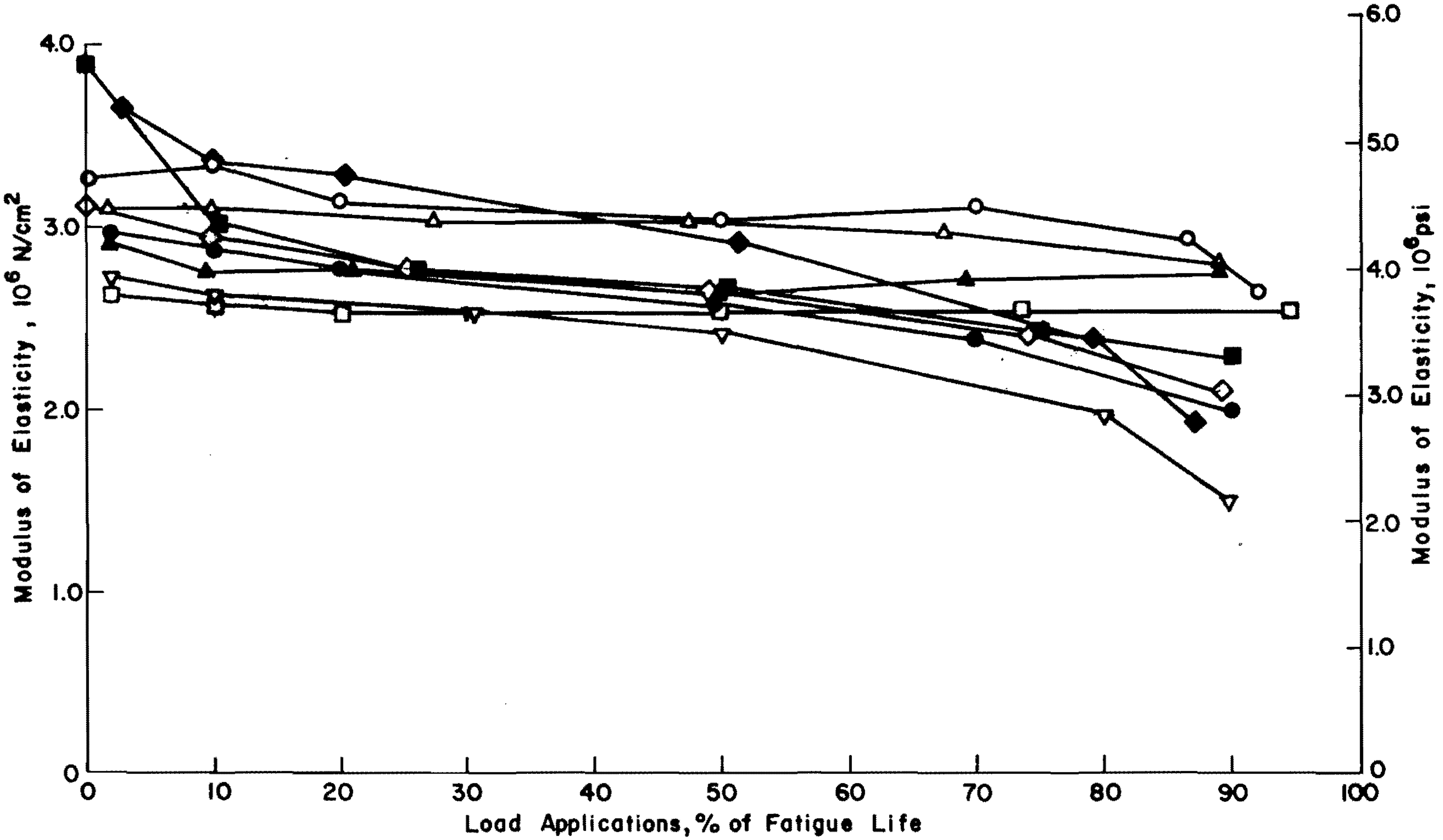


Fig 12. Relationships between modulus of elasticity and load applications for specimens from Project 2E-1.

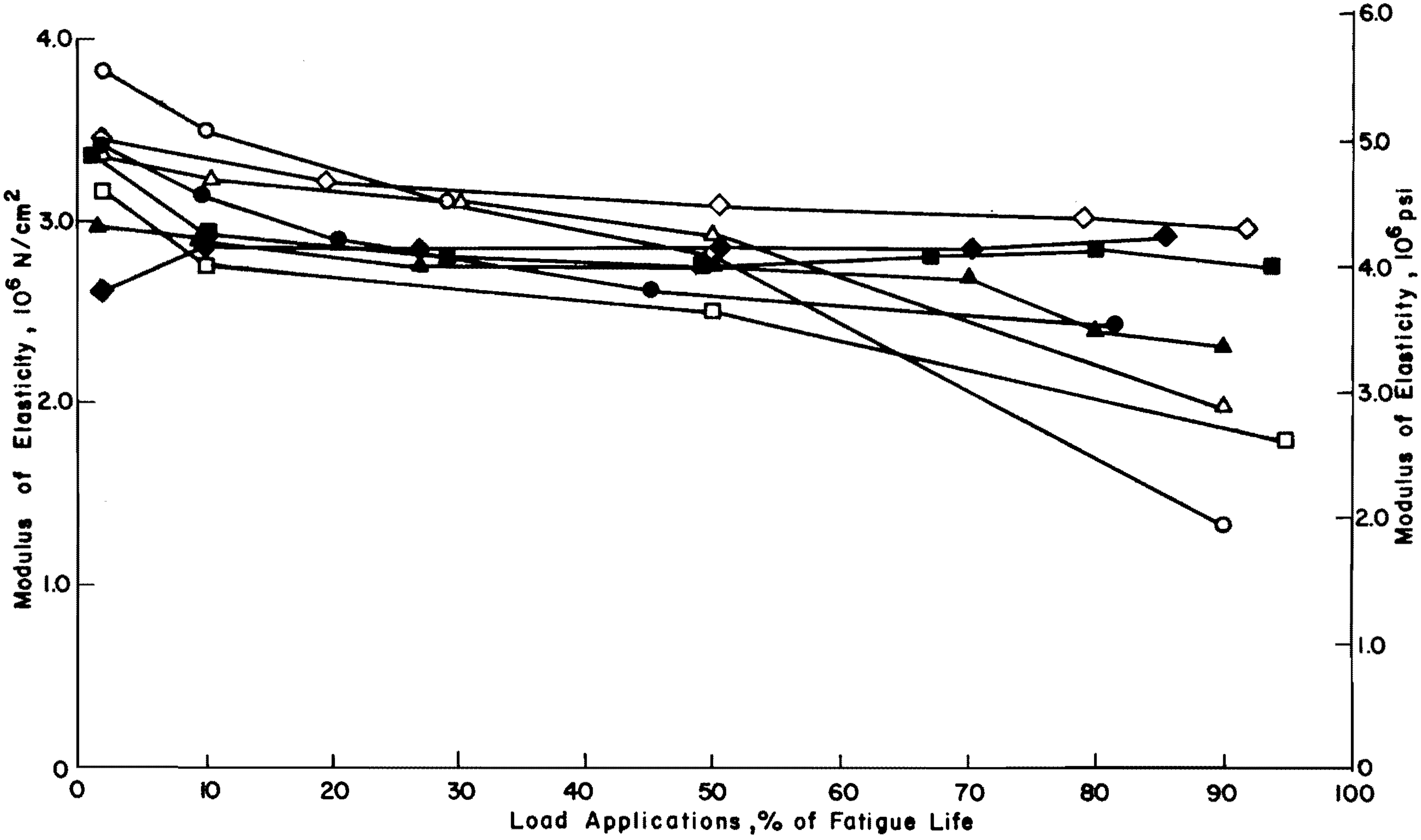


Fig 13. Relationships between modulus of elasticity and load applications for specimens from Project 2E-2.

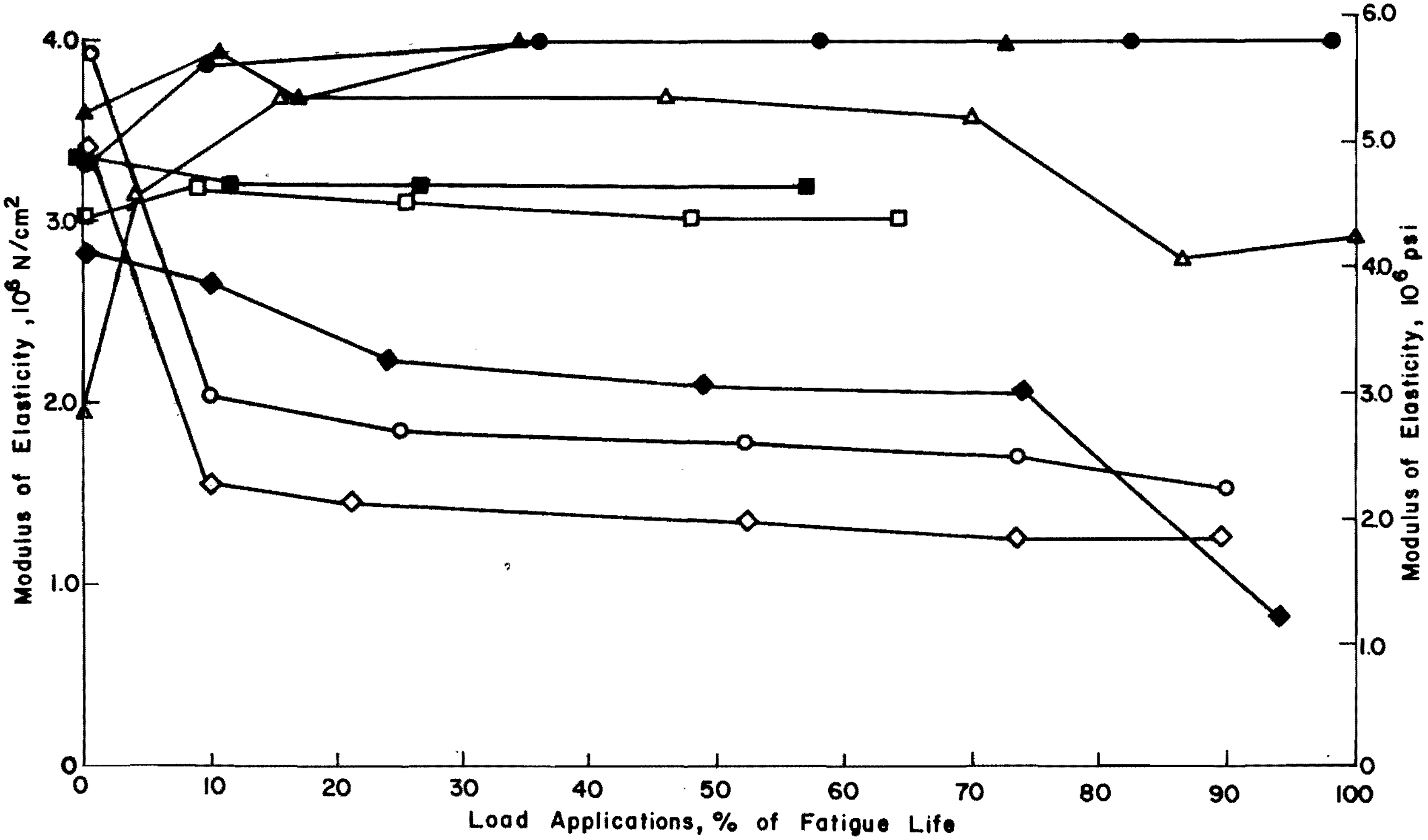


Fig 14. Relationships between modulus of elasticity and load applications for specimens from Project 17B.

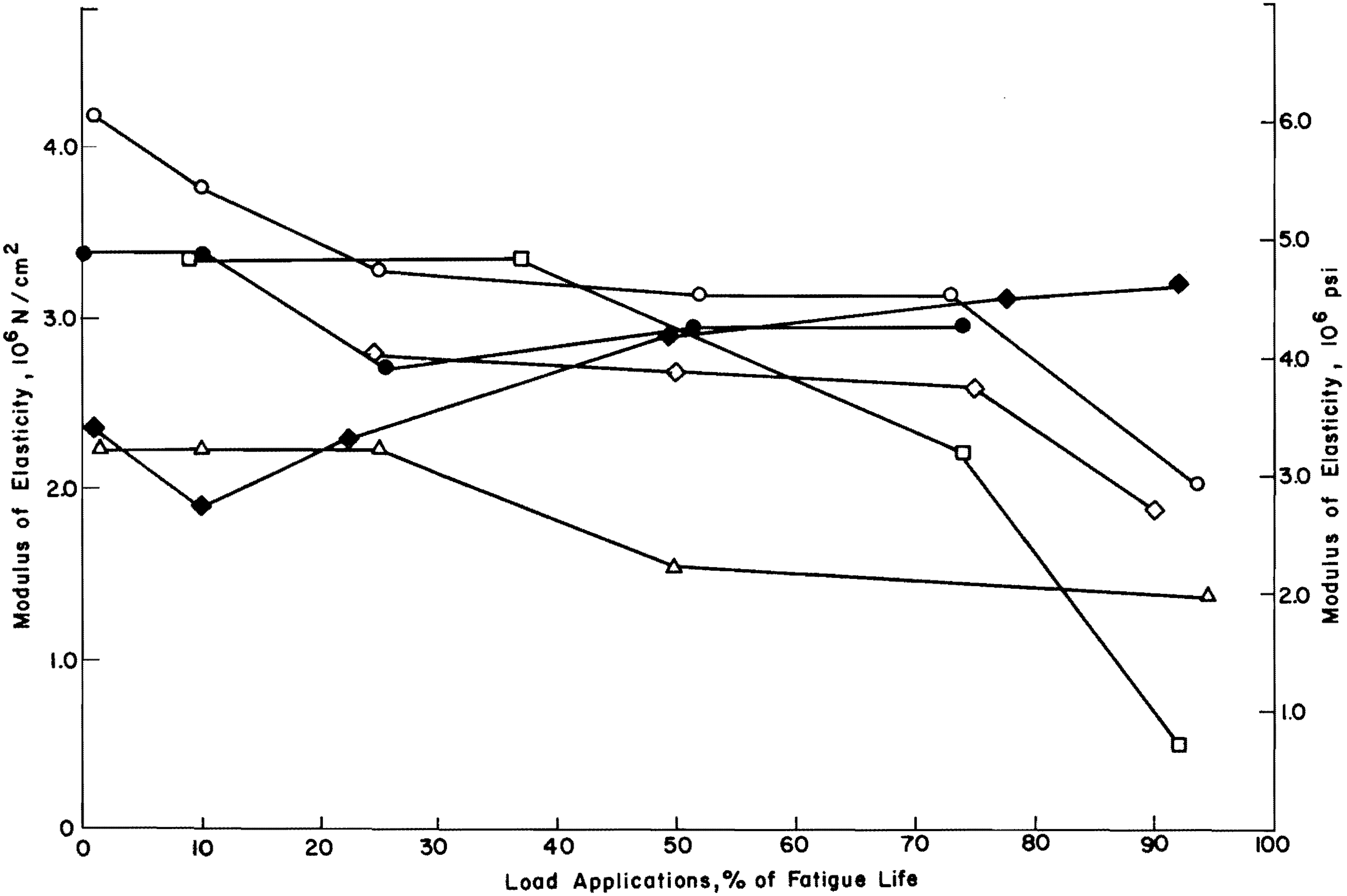


Fig 15. Relationships between modulus of elasticity and load applications for specimens from Project 17M.

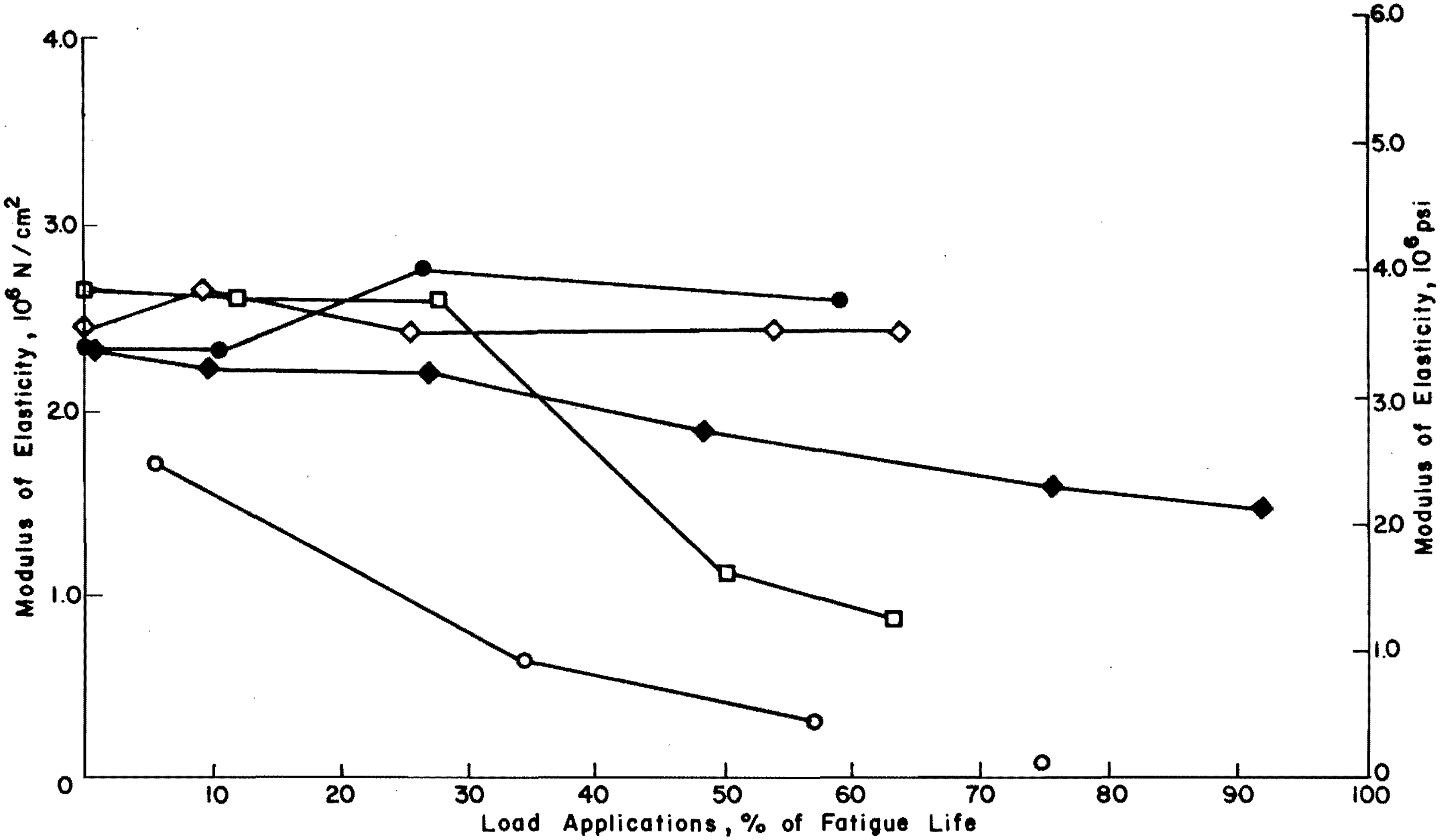


Fig 16. Relationships between modulus of elasticity and load applications for specimens from Project 19B.

was near ultimate failure. The results of the other three projects show a similar overall behavior, although the results for individual specimens were more erratic.

The means of the modulus of elasticity at selected percentages of fatigue life are given in Table 9. The coefficients of variation for the specimens from Project 2E are much smaller than from the other series, as is indicated in the graphs. For Project 2E, the decrease in mean modulus between 10 and 90 percent of the fatigue life was approximately 23 percent. The remaining projects apparently were experiencing seating difficulties during the first 20 percent of the load applications, as evidenced by very erratic behavior in this region. For this reason, the first 20 percent of the load cycles was ignored. Between about 25 and 75 percent of the fatigue life, the mean modulus decreased 3, 14, and 38 percent for Projects 17B, 17M, and 19B, respectively.

From the available data, it appears that the three normal weight aggregate concretes exhibit similar overall behavior with regard to decreasing modulus of elasticity but that the amount of the decrease varies according to the particular project. The concrete containing iron ore slag, Project 19B, showed much larger decreases in modulus for given percentages of fatigue life. Definite conclusions concerning Projects 17B, 17M, and 19B are difficult because of the large variations in the results and the limited amount of data available.

TABLE 9. MEAN MODULUS OF ELASTICITY VALUES AT SELECTED PERCENTAGES OF THE FATIGUE LIFE

Series	% N_f	Mean Modulus, 10^6 N/cm^2	Mean Modulus, 10^6 psi	Coef. Var., %	% N_f	Mean Modulus, 10^6 N/cm^2	Mean Modulus, 10^6 psi	Coef. Var., %	% N_f	Mean Modulus, 10^6 N/cm^2	Mean Modulus, 10^6 psi	Coef. Var., %
2E	10	2.97	4.31	9.0	50	2.75	3.99	7.1	90	2.28	3.30	21.7
17B	25	2.83	4.10	32.4	50	2.80	4.06	34.9	75	2.74	3.97	39.8
17M	25	2.68	3.89	18.6	50	2.59	3.76	24.0	75	2.30	3.34	40.9
19B	25	2.08	3.01	37.0	50	1.65	2.40	54.0	75	1.28	1.86	77.0

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the findings of a study to characterize the elastic and fatigue behavior of inservice portland cement concrete subjected to repeated loads using the indirect tensile test. Included in the study were the development of stress-fatigue life relationships, determination of elastic modulus under repeated load, and estimation of the variation of the material properties. In addition, an effort was made to establish a relationship between tensile strength and fatigue life.

CONCLUSIONS

Fatigue Life

(1) The semilogarithmic relationships between fatigue life and stress/strength ratio for the inservice concrete could be expressed in the form

$$\log N_f = C_1 S + C_2$$

where

N_f = fatigue life,
S = stress/strength ratio, percent,
C_1 = slope of the semilogarithmic relationship, and
C_2 = intercept of the semilogarithmic relationship.

(2) For the four projects tested, the slopes of the semilogarithmic relationships were essentially equal, with values of C_1 ranging from -0.082 to -0.109. Intercept values C_2 ranged from 8.48 to 11.4. The slope values compare favorably with values of previous studies on laboratory-prepared specimens; however, intercept values were less, resulting in lower fatigue lives for the inservice concrete.

(3) The variations with respect to the semilogarithmic fatigue life relationships for the three projects using normal weight aggregates were very consistent, as indicated by a range in the standard error of the estimate of 0.76 to 0.87. For the light-weight aggregate concrete, the standard error of the estimate was 1.12.

(4) Previous studies have indicated that the fatigue life and stress/strength ratio relationship is essentially the same for the projects tested. In this study the fatigue life relationships were not the same; however, a small error in the estimated strength could account for the differences. Thus, it is felt that additional tests should be conducted before a definite conclusion is made.

Modulus of Elasticity Under Repeated Loads

(5) The modulus of elasticity of concrete decreased with an increase in the number of repeated loads. The magnitude of the decrease ranged as high as 40 percent over the usable life of the concrete, but was different for the various projects. A significant decrease often occurred at about 75 percent of the fatigue life.

(6) The variation in modulus for the projects tested is project and material dependent. The coefficient of variation for the resilient modulus of elasticity increased with increasing load applications. At 50 percent of the fatigue life, coefficients ranged from 7 to 54 percent.

Tensile Strengths

(7) The tensile strengths for capped specimens of the projects tested ranged from 362 to 491 N/cm^2 (525 to 712 psi).

(8) The coefficients of variation of the capped tensile strengths ranged from 8 to 16 percent.

RECOMMENDATIONS

(1) If extensive repeated-load tests are to be conducted, equipment capable of recording at much higher deformation rates than the present equipment should be obtained. Testing could be completed in less time or the number of specimens tested could be increased.

(2) All concrete field cores should be capped before testing under repeated loads in order to minimize the variation due to testing.

(3) Further investigation is probably needed to determine if the fatigue behavior of paving concretes in Texas is essentially the same when analyzed on the basis of fatigue life and stress/strength ratio. If the relationships are similar then fatigue life could be estimated on the basis of static tests or the pavement could be designed to reduce the applied stress to a level which would allow a prescribed number of loads to be carried.

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APPENDIX A

SUPPLEMENTAL DATA - CURRENT STATUS OF KNOWLEDGE

TABLE A-1. VARIATIONS IN COMPRESSIVE STRENGTH FOR 28-DAY-OLD PAVING CONCRETE TESTED IN WEST VIRGINIA RESEARCH PROJECT (Ref 24)

Project Number	Mean Compressive Strength		Overall Standard Deviation		Overall Coefficient of Variation, %
	N/cm^2	psi	N/cm^2	psi	
1	3223	4675	376	545	11.7
2	2589	3755	290	420	11.2
3	2565	3720	396	575	15.5
4	3282	4760	322	467	9.8
5	3232	4688	505	733	16.5

TABLE A-2. VARIATIONS IN COMPRESSIVE STRENGTH OF SAWED FIELD SPECIMENS USED IN RESEARCH BY STATE DEPARTMENT OF HIGHWAYS OF COLORADO (Ref 25)

Cores Taken from Interstate 270

	Bottom of Cores		Top of Cores	
	Taken from Path of Vibrators	Taken Between Vibrators	Taken from Path of Vibrators	Taken Between Vibrators
Mean compressive strength, N/cm^2 (psi)	3712 (5384)	3538 (5132)	3234 (4691)	2901 (4208)
Standard deviation, N/cm^2 (psi)	841 (1220)	779 (1130)	655 (950)	841 (1220)
Coefficient of variation, %	22.6	22.0	20.2	29.0

Cores Taken from Interstae 805

	Bottom of Cores		Top of Cores	
	Taken from Path of Vibrators	Taken Between Vibrators	Taken from Path of Vibrators	Taken Between Vibrators
Mean compressive strength, N/cm^2 (psi)	3132 (4543)	2844 (4125)	2752 (3992)	2542 (3687)
Standard deviation, N/cm^2 (psi)	345 (500)	310 (450)	427 (620)	234 (340)
Coefficient of Variation, %	11.0	10.9	15.5	9.2

APPENDIX B

S-N RELATIONSHIPS FOR VARIOUS PROJECTS

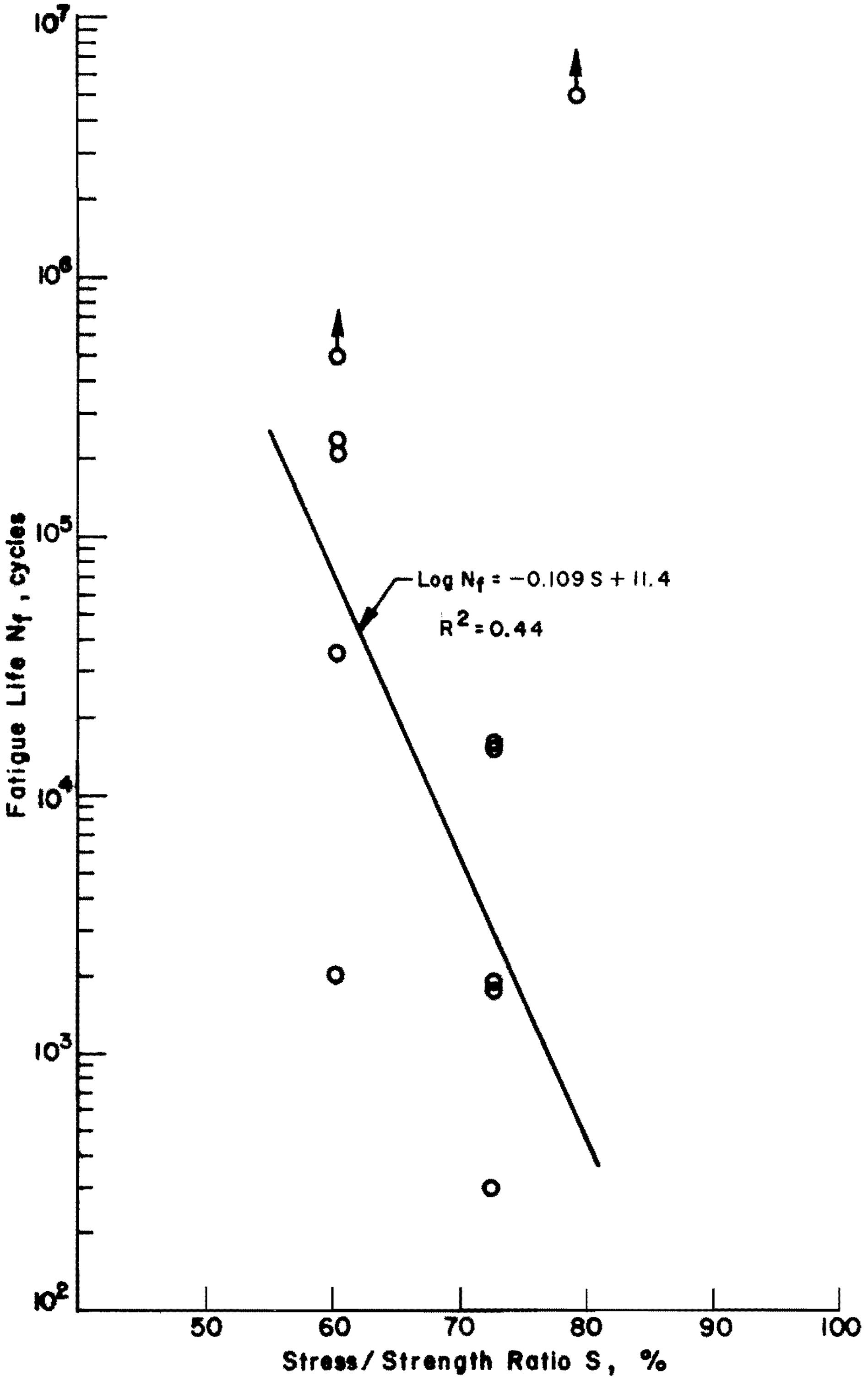

Fig B-1. S-N relationship for Project 17B.

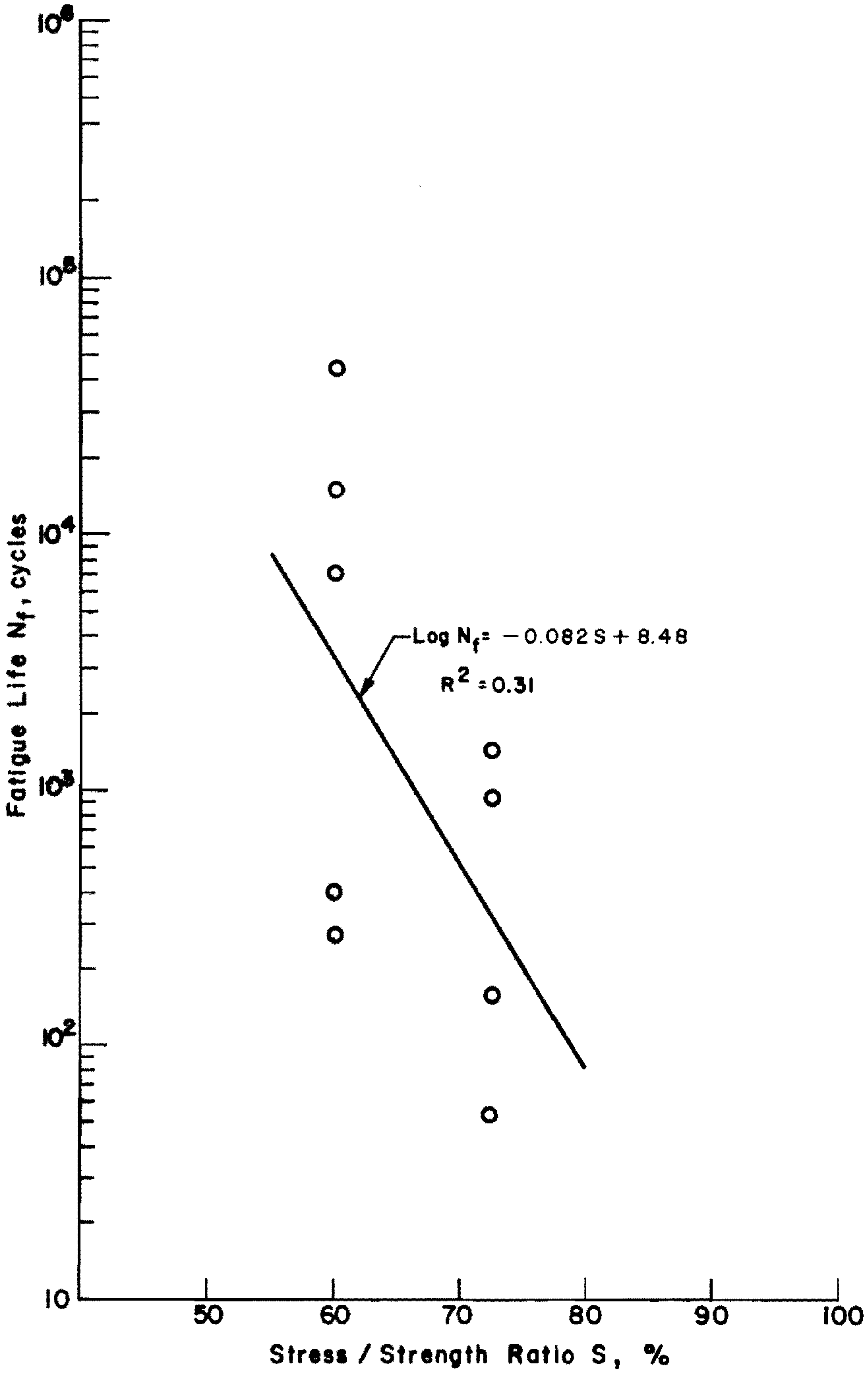

Fig B-2. S-N relationship for Project 17M.

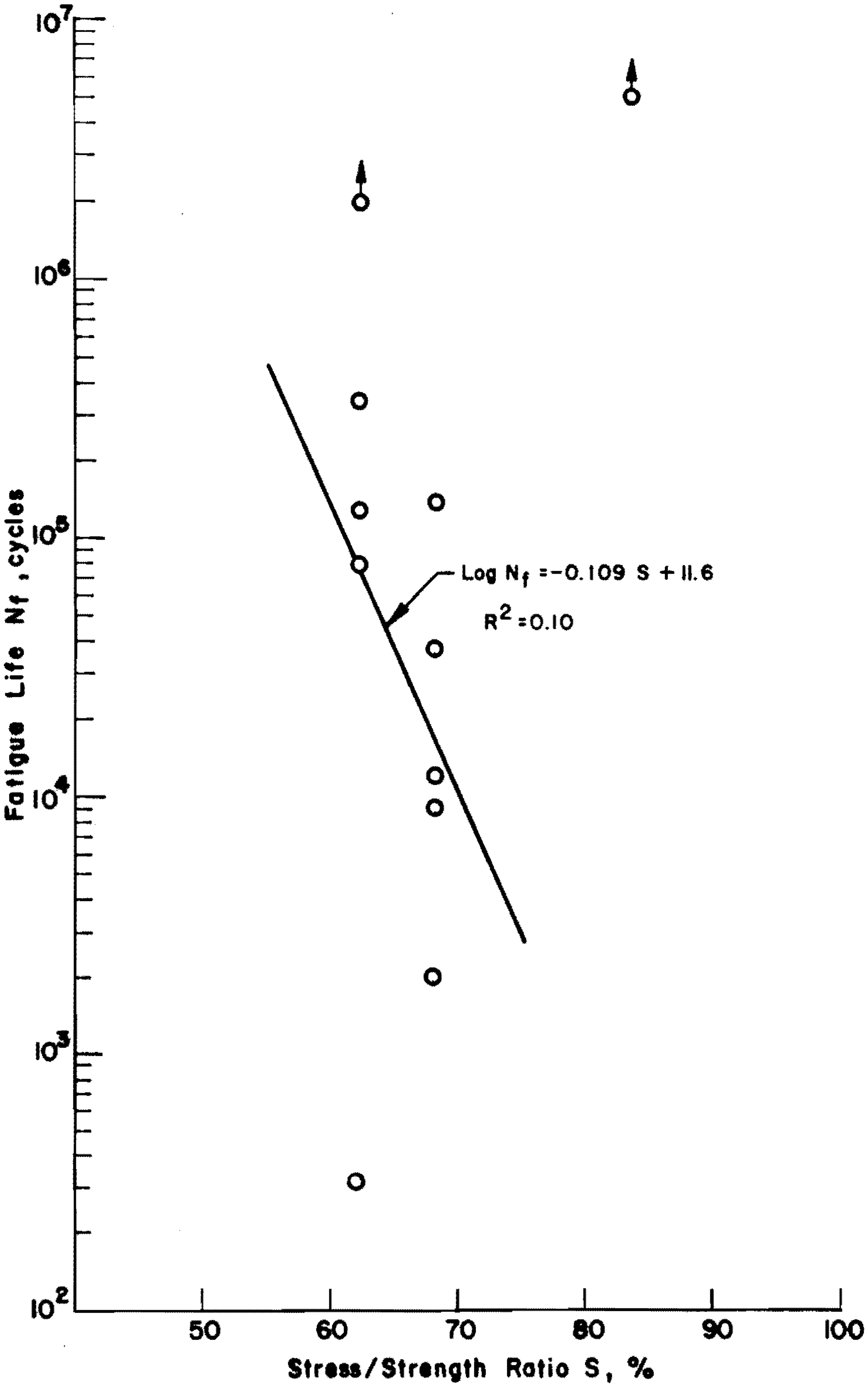

Fig B-3. S-N relationship for Project 19B.