DURABILITY OF CONCRETE AND CONCRETE STRUCTURES BY SLOW CYCLE FATIGUE

By

ARNOLD WILSON

Bachelor of Engineering Science
Brigham Young University
Provo, Utah
1957

Master of Science
Brigham Young University
Provo, Utah
1962

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
December, 1973

DURABILITY OF CONCRETE AND CONCRETE STRUCTURES

BY SLOW CYCLE FATIGUE

Thesis Approved:

John P. Lloyd
Thesis Adviser

Robert L. Janes

[illegible]

Gerald Bruzewitz

N N Durham
Dean of the Graduate School

PREFACE

This dissertation is concerned with establishing a method of test which can be used to measure the durability of concrete. The test can be conducted on hardened concrete specimens in a few days. The method of test has demonstrated merit for measuring the durability of concrete which has been subjected to freezing temperatures during the initial curing period.

The author wishes to express his gratitude to Dr. R. L. Janes, Chairmen of the Advisory Committee, Dr. John P. Lloyd for his assistance and critical review and recommendations, and to the other Committee members for their review and suggestions.

Appreciation is also expressed to the following graduate students who assisted in preparing and testing concrete samples, the results of which gave support to this dissertation: Kwang-Tien Hou, Che-Ming Hu, M. S. Chaurushia, M. P. Vhora, Harikishna G. Upadhyaya, Purushottam B. Mehta, Ashvini K. Pandit, Vernon L. Anderson, H. J. Doshi, Tang Yuan Lee, and Dinesh J. Doshi.

The author wishes to express his appreciation to the Civil Engineering Department and the Research Department at the Brigham Young University for financial support and for the use of laboratory space and equipment making this research possible.

Finally, I would like to express appreciation to my wife and children who persisted with patience and understanding making this dissertation possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Statement of Problem

The broad use of portland cement concrete as a construction material has been stimulated by qualities exhibited in its many applications. But since concrete is manufactured locally, its quality varies depending upon the care and concern of those responsible for its manufacture. Extreme variation in the final product has resulted in the need for quality control specifications. When such specifications are lightly considered or ignored, it is necessary to instigate thorough inspection and testing to assure a quality concrete.

Further, many field operations are not in keeping with good concrete practice. In particular, concrete is often placed when outside temperatures are below freezing. The following example may help to illustrate. During the winter of 1961 and 1962 a five-story reinforced concrete and masonry structure was being constructed. One large foundation wall was placed during an afternoon when the temperature of the air was 32°F. The forms were filled and left exposed without coverings or heat. The temperature of the air reached a minimum of 6°F during the night and was 10°F at the time the forms were stripped the following day. Heavy frost was visible on the concrete.

Approximately 28 days later core samples taken from the foundation wall exhibited an average compressive strength of 3000 psi. Concrete of the same mix design used in other locations and cured under more favorable conditions had strengths near 5000 psi.

Compressive strength of concrete is frequently used as an overall measure of concrete quality since it has been shown to be closely related to such concrete quality characteristics as permeability, creep, fatigue strength and freeze-thaw durability. Early freezing has been found to influence the compressive strength (1, 2, 3, 4, 5).* It is reasonable to expect that other properties will also be altered by freezing. One such property is slow cycle fatigue durability. This study is concerned with the relationship of slow cycle fatigue durability to overall concrete quality.

1.2 Purpose of Investigation

The purpose of this investigation was to develop a fatigue testing method which would relate to the fatigue durability of portland cement concrete. In particular the program considered a study of the following:

1. The influence of low temperature curing on the response of concrete to low frequency, high intensity cyclic compressive loads.

2. The influence of freezing of fresh concrete on the development of internal flaws, both those formed during the curing period and those formed as a result of applied loading.

---

*Numbers in brackets refer to references listed in the Bibliography.

3. The influence of entrained air on the response of concrete subjected to slow cycle fatigue loading.

4. The development of a quantitative means of measuring the fatigue durability of concrete by relating to a durability factor and to the number of load cycles to cause complete failure.

5. Application of the fatigue testing method to an actual concrete structure which had concrete of questionable quality.

1.3 Definitions

The following definitions will apply throughout this report:

1. Fatigue durability: In general fatigue durability is defined as the ability of concrete to resist or withstand, for the life of the structure, all intended loads without excessive deterioration or failure. More specifically, in this report, durability is a relative measure of the resistance of concrete to cyclic uniaxial compression.

2. Cool curing: Curing conditions during which the ambient temperatures are near freezing but not low enough to cause significant freezing within a specimen.

3. Bond cracks: Cracks or discontinuities between the paste matrix and the coarse aggregate which are either microscopic or macroscopic.

4. Fresh concrete: Concrete immediately after placing and before final set has occurred. Such concrete is in a plastic condition.

5. Cycles to failure: As the slow cycle fatigue test was performed the number of cycles was automatically counted. Cycles to failure refer to the total number of load cycles at the time of complete structural failure of the specimen.

6. Durability factor: The durability factor was calculated from the following equation:

$$DF = \frac{P_c N_i}{M}$$

where P_c = ratio of the dynamic Young's modulus of elasticity at N cycles of dynamic load to the dynamic modulus at N = 0 cycles of load, indicated as a percentage.

N_i = number of cycles at which P_c reaches the specified minimum value for discontinuing the test (taken to be 80%) or the specified number of cycles at which the cyclic load is to be terminated (taken to be 1800 cycles);

M = specified number of cycles at which the dynamic load was to be terminated. In this investigation, M = 1800 cycles was used (for further details refer to Appendix A).

7. Autogenous healing: Fine cracks in concrete will heal under moist conditions. This autogenous healing is probably due to continued hydration of unhydrated cement.

CHAPTER II

HISTORY OF RESEARCH

2.1 Effects of Early Freezing

The temperature of concrete during initial curing has an important influence on its strength and durability at later ages. NcNeese (1) found that concrete which was frozen in a plastic state and later allowed to cure under standard conditions, lost up to 50 percent of the standard compressive strength. He further found that if the concrete temperature was 75°F at the time of placing, it must be subjected to severe freezing within six hours for any appreciable damage to occur. If the concrete temperature was 40°F at the time of placing, even a mild freezing temperature of 25°F resulted in a 50 percent reduction in strength.

Other laboratory tests (1, 2, 3) and field tests (4) of concrete subjected to freezing temperatures show that such concrete usually fails to develop its full compressive strength.

The mechanism of such failure to develop full strength is not completely known, but from present evidence (5) it appears that microfractures are formed in the binder as a result of expansion due to freezing of the water in the pores of the concrete. These microfractures bring about a loss in unit weight in the concrete, reduction in adhesion of the particles, lower resistance to abrasion, and reduction in the tensile strength and elasticity of the concrete. There is also an increase in the permeability of the concrete which in turn accentuates other harmful effects and brings about progressive deterioration of the concrete.

However, not all research has shown such definite detrimental results produced by the freezing of fresh concrete. For example, H. M. Fitch (2) has reported that concrete, after freezing, will begin to develop strength at the normal rate if the concrete contains adequate moisture and is subjected to thawing temperature. Fitch concluded that if the freezing period were omitted in the plotting of the age-strength curves, the curve would be essentially the same as though the concrete had never been frozen.

Young (6) indicated that for concrete frozen while still plastic, the strength and durability were nearly always affected and that the compressive strength was usually reduced 10 to 50 percent. He also observed that internal examination of the concrete that was frozen while still plastic showed evidence of the formation of ice crystals which appeared as "little turkey tracks."

Hagy (7) reported that in 1930 some footings were placed in near zero weather with no attempt to protect the concrete. After three weeks the concrete thawed and seemed to be as plastic as when poured. Cylinders were made at the time the footings were poured and protected from freezing. Additional cylinders from the frozen concrete were made and cured after it became plastic. After a six-month period, there was not over a five percent difference in the compressive strength of the two concretes.

However, sufficient compressive strength is no guarantee that early freezing has not adversely affected another concrete parameter such as fatigue durability. An example may help to illustrate: A structure was a reinforced concrete frame carrying a 24-inch water main across a canal. After 21 years of service the structure had deteriorated to the point that extensive repairs were required to save it. The legs had buckled slightly and portions of the deck had dropped into the canal. The parapets each side of the pipe were commencing to spall. Some of the surface of the concrete was in even worse condition with much steel exposed. In places daylight could be seen through the core concrete behind the main bars. A study of the engineer's records indicated snow and ice during part of the construction period with temperatures as low as 15°F. The investigation pointed to a progressive internal weakening of the concrete (11).

The literature contains numerous examples of structural failures which were the result of having loads applied to concrete which was frozen and which had insufficient strength at the time of loading (9, 10, 11, 12). A recent example occurred during the construction of a 16-story senior citizens' residence in Calgary, Canada. The roof slab forms were removed 28 days after casting the concrete. The following day a large portion of the roof collapsed. Standard cured cylinder strengths averaged 3670 psi, while the compressive strength of samples taken from the collapsed structure had an average strength of 311 psi. The collapsed slab had been enclosed and heated three days after casting; however, the top surface was left exposed to temperatures that averaged 19°F above zero during the 28-day curing period. The average daily wind was 11 mph. The combination of low temperature and chill factor effect of the wind delayed the hydration of the cement, resulting in very low concrete strength. (10).

In order to prevent failures of concrete structures, the concrete needs to be evaluated as the construction of the building progresses. Determination of the compressive strength of the concrete has usually been used to evaluate the quality of the concrete. The method of evaluating the compressive strength of concrete is simple and inexpensive. The compressive strength is in itself an important property and is related to many of the other physical properties of concrete. However, the behavior of concrete under some loading and exposure conditions may not be directly related to the compressive strength. For example, consider concrete exposed to extreme freeze and thaw conditions. The simple addition of entrained air will increase the durability under these conditions many times, yet the compressive strength can be essentially the same. Therefore, to correctly determine the influence of early freezing, it is important to evaluate other properties in addition to the compressive strength.

2.2 Durability of Concrete

Deterioration of concrete may result from inherent weakness within the concrete, from the action of internal forces produced by exposure to the environemnt, or from external loadings. ACI Committee 201, working with concrete durability, has presented a summary of the current knowledge on durability of concrete in service. The committee listed durability problems and explained the basic mechanisms of deterioration and suggested proportioning, placing, curing, and maintenance practices best suited to overcome the difficulties of producing durable concrete (13). The best means of producing durable concrete is thus well known though the techniques are not always followed in practice.

While ACI Committee 201 has been deeply concerned with concrete durability and ACI Committee 215 with concrete fatigue, there exists a joint area of fatigue durability which may prove beneficial for further study and research. The deteriorating influences of cyclic loads on concrete with suspect quality needs further investigation. As an example, concrete which has been subject to early freezing conditions may have induced flaws which create stress concentrations, that seriously alter the fatigue durability under the influence of cyclic loads.

2.3 Dynamic Modulus of Elasticity

Whitehurst (14), author of the ACI Monograph No. 2, considers the use of various sonic tests to evaluate certain properties of concrete. He presents a brief history of sonic methods and discusses the application and accuracy of sonic test procedures.

The sonic test, sometimes referred to as the resonant frequency test or the dynamic test, quickly done and has the advantage that the dynamic modulus of elasticity can be determined without damaging the specimen. Such sonic tests have been used for many years to evaluate the general quality of a concrete or to compare quality levels of different concretes. The resonant frequency of the specimen, measured in the sonic test, varies with the number of internal flaws. With an increase in flaws in a concrete specimen, there is a decrease in the resonant frequency of the specimen.

The nondestructive nature of the tests allows the influence of various parameters on the sonic modulus to be studied with respect to time. It has been found (14, 15, 16) that the disintegrating effects of freeze-thaw cycles can be detected earlier with the dynamic modulus method than with other available methods. Because the dynamic modulus test can be utilized to study the behavior of concrete under various conditions of load or environmental exposure, it is an appropriate test to investigate the deteriorating influence of cyclic load. For further details and calculations, refer to Appendix A.

A plot of the dynamic modulus of elasticity vs. the number of cycles of freeze and thaw shows graphically the rate at which a concrete specimen is disintegrating. The calculation of both the durability factor and the dynamic modulus of elasticity established by the resonant frequency of the specimen has long been a part of the freezing and thawing tests presented by A.S.T.M. C290-67 and C291-67 (30). With a fatigue tests there occurs a progressive deterioration and breakdown of the specimen due to an increasing growth of internal flaws. Such deterioration is similar to the progressive deterioration of freeze-thaw specimens.

Therefore, the proposed slow cycle test method can produce test results that can be evaluated by both the graphical plot of the dynamic modulus vs. the number of cycles of load and the durability factor to determine fatigue durability.

2.4 Fatigue of Concrete

When concrete fails under a number of repeated loads, each smaller than the single static load which would cause failure, it is said to have failed in fatigue.

ACI Committee 215 (17) has published a comprehensive bibliography on the fatigue of concrete. This bibliography lists the major technical periodicals, bulletins, and tests, both foreign and domestic. Further, it lists studies of compressive and flexural fatigue loading of plain and reinforced concrete and also of the resistance of bond to fatigue loading.

Fatigue strength of concrete is known to be lower than its static strength and this may well be due to the formation and development of internal cracks. Many investigations have shown that the resistance of plain concrete to a very large number of repeated compressive loads is approximately 50 to 55 percent of the static ultimate (17). The number of repetitions that concrete can resist decreases rapidly as the maximum stress increases. Approximately 5000 repetitions of load at 70 percent of the nominal ultimate load are required to cause failure (18).

ACI Committee 215 indicated the need for more research in almost every phase of concrete fatigue. The committee report says that information is needed on the effect of moisture, aggregate bond, different aggregates, air entraining, admixtures, curing, rest periods, microcracks in the paste, different environments of corrosive agents, specimen size, range of stress, combined loading, accumulative fatigue damage, freezing and thawing, and previous stress histories.

2.5 Slow Cycle Fatigue

Most of the past fatigue research has utilized a constant loading frequency in the range of 10 to 800 cycles per minute (17). Slow cycle fatigue for the purposes of this report is defined to have a loading frequency ranging from 1/2 to 3 cycles per minute. The higher frequency range is a result of the response rate of the testing equipment used.

Slow cycle fatigue test data within the range of 1/2 to 3 cycles per minute is essentially nonexistent in the literature. The relationship to durability of a durability factor or of a changing dynamic moculus as a result of cyclic loading has not been applied in a meaningful way with fatigue testing. Therefore, a brief history of slow cycle fatigue research conducted at the Brigham Young University is here presented.

In 1964, research sponsored by Brigham Young University, was conducted to evaluate concrete frozen while in a plastic condition. Results of this research indicated an internal deterioration under cyclic loading progressing at a faster rate than for concrete not subjected to freezing. An extension of this research was used to separate many of the variables and to verify and extend the original results. Several graduate students in the Department of Civil Engineering conducted further research on frozen concrete by using the slow cycle fatigue method under supervision of the author. Variables such as size of specimen, moisture content at the time of test and extent of freezing required special handling of the specimens and to the development of special apparatus used at the time of test (19, 20). Additional research brought to light the effects of type of cement, type and amount of loading, and effect of real atmospheric curing conditions (21, 22, 23). Later microscopic investigations were conducted to study the effects of freezing of fresh concrete as well as the progressive deterioration which resulted from cyclic loading (24, 25).

As the research progressed, confidence in the technique and approach also increased. It was evident from the beginning that a testing program which could be used to evaluate concrete samples taken from construction projects was the ultimate goal for developing a slow cycle fatigue testing method. As a part of the total fatigue testing program, concrete samples from construction projects were obtained and tested according to the fatigue method previously developed. This testing program also included a microscopic evaluation of the concrete samples.

Continuing research has provided additional information with regard to fatigue durability; (a) for variations in concrete consistency with a constant water-cement ratio (26); (b) for variations in the percentage of entrained air and, (c) for variations in the rate of load application (27).

The limited size and capacity of the freezing units used in the laboratory made it difficult at times to maintain suitable temperatures for freezing. At times it was felt that only the surface of the fresh concrete had been damaged. It has been observed that smaller specimens (4 x 8 in. cylinders) showed more consistent results than larger specimens (6 x 12 in. cylinders). Careful control of the freezing as well as of other factors resulted in consistent determination of change in the durability factor and number of cycles of load causing failure (28).

With due regard to the development of equipment and techniques, the more significant results of the above research have been presented at this time and are included in the results of this report.

CHAPTER III

EXPERIMENTAL DETAILS

3.1 General

In search of a suitable test method which could be used to evaluate the damage sustained by concrete subject to freezing, it was decided to subject specimens which had been frozen while plastic, thawed, and standard cured, to a slow cyclic compressive load. Both a plot of the dynamic modulus of elasticity vs. the number of cycles of load and a durability factor were used to determine if the cyclic load was producing any significant internal change. In addition, the total number of cycles of load producing complete failure was recorded and used as an indicator of the concrete fatigue durability.

Tests performed on specimens frozen while still plastic were used as a means of evaluating the fatigue method of test. This evaluation becomes meaningful only when the results of tests on specimens frozen and those not frozen but taken from the same batch of concrete are compared. For simplification in presenting the results and for describing the procedure, the frozen specimens, which were later cured under standard conditions, will be referred to as damaged and those specimens cured entirely under standard conditions will be referred to as nondamaged or standard cured.

As the research progressed it was observed that there was a significant difference in the number of cycles to failure and the rate at which the dynamic modulus changed between the damaged specimens and the non-damaged or standard specimens. However, during the initial periods of research, the results were found to be irregular and difficult to reproduce. In particular, it was noted that as a specimen became drier, it required a greater number of cycles of load to produce a given change in the dynamic modulus of elasticity.

In order to obtain more consistent results, it was decided to do all dynamic testing with the specimens in a saturated condition. In addition, it was also decided to submerge all specimens in water for 48 hours prior to starting the cyclic load test.

Another problem encountered early in the research program was the need for a decision on the amount of load to apply. Following pilot testing during which the peak cyclic load was varied between 35 and 90 percent of the ultimate compressive strength on different samples, the figure of 70 percent of the ultimate load was arbitrarily selected for most of the testing. It may be found from future testing that a peak cyclic load value other than 70 percent will prove more economical of testing time and still give reliable results.

The entire research was initiated to study and evaluate the effects of freezing temperatures during the early curing period on the fatigue durability of concrete. In order to properly evaluate the freezing effect on the concrete, it was necessary to try to isolate some of the variables. Specific parameters which have been studied include: (1) rate of load application, (2) variation in the maximum and minimum values of cyclic load, (3) variations in air content, and (4) age at the time of test. Additional studies were made to determine the effect on compressive strength caused by freezing fresh concrete. For evaluation of these factors a microscopic evaluation of the concrete was used to further clarify the physical phenomenon associated with early freezing and the slow cycle fatigue type of failure. In addition, the durability factor and the number of cycles to failure for concrete cast on the job site under freezing conditions was compared to similar results obtained from the laboratory investigation.

3.2 Materials

Local coarse and fine aggregates used in the concrete were hard limestone or dolomite. The aggregates used were obtained from local commercial sources and met ASTM requirements (31).

Specific gravity values for both fine and coarse aggregates were 2.6. For the type I and type III portland cement the specific gravity was assumed 3.15.

The maximum size of coarse aggregate was 3/4 in. and the maximum size of fine aggregate was 3/16 in.

The mixing water used was from the local culinary water system. The liquid air entraining agent was dispersed in the mixing water prior to mixing in the concrete. The pressure method was used to determine the amount of air entrained in the concrete.

Prior to testing all specimens were capped with a sulfur compound approximately 3/16 in. thick.

3.3 Description of Specimens

Specimens cast in the laboratory and subject to the slow cycle fatigue test were either 4 in. in diameter by 8 in. in height or 6 in. in diameter by 12 in. in height.

Core specimens 3 3/4 in. in diameter and generally 8 in. long were cut perpendicular to their axis at both ends and capped with sulfur compound approximately 3/16 in. thick.

Most of the concrete core specimens were obtained from the foundation of a large reinforced concrete and masonry building, parts of which were constructed in freezing weather during 1962 and 1963.

One-inch thick samples from the cylindrical test specimens were obtained for microscope examination by cutting with a masonry saw equipped with a diamond blade. The cut samples were polished in a rotary polishing machine.

3.4 Fabrication and Curing

The concrete mixes were proportioned by weight of ingredients based upon a trial mix design method. Proportions varied depending upon the water-to-cement ratio and the air entrainment used. For specific proportions refer to Appendix C.

The concrete was mixed in a stationary horizontal pan concrete mixer. The concrete was placed in the specimen molds within 15 minutes from the time all ingredients were added to the mixer.

Curing of the laboratory specimens was varied in order to study the resulting effects. For details refer to Appendix C.

In order to establish uniformity as well as standardize the test procedure, a majority of the specimens were cured in one of two ways:

(1) Standard curing condition. A portion of the specimens from each batch was cured in air for 24 hours at 70°F. After removing the molds the specimens were placed in a fog room to cure at 73°F and 90 percent humidity until time for testing. All specimens subject to cyclic loading were immersed in water 48 hours prior to testing.

(2) Early freezing condition. The remaining specimens from each batch were cured in air at 70°F for six hours. The molds were stripped and the specimens placed in a freezer unit for 24 hours at -10°F. After removal from the freezer the specimens were placed in the fog room at 73°F and 90 percent humidity until 48 hours before time of test at which time the specimens were immersed in water.

Specific variations to the above curing conditions may be noted in Appendix C.

3.5 Equipment

The major equipment used in performing the slow cycle fatigue tests is listed below.

1. Universal testing machine with a 300,000 lbs. static capacity and cyclic load control. See Figure 1.

2. Sonic Modulus equipment for determining the dynamic modulus of elasticity. See Figure 2.

3. A commercial freezer unit capable of temperatures 0° to -13°F with a 15 cu. ft. capacity.

4. Horizontal pan concrete mixer with a capacity of 2 cu. ft.

5. Masonry saw equipped with diamond blade.

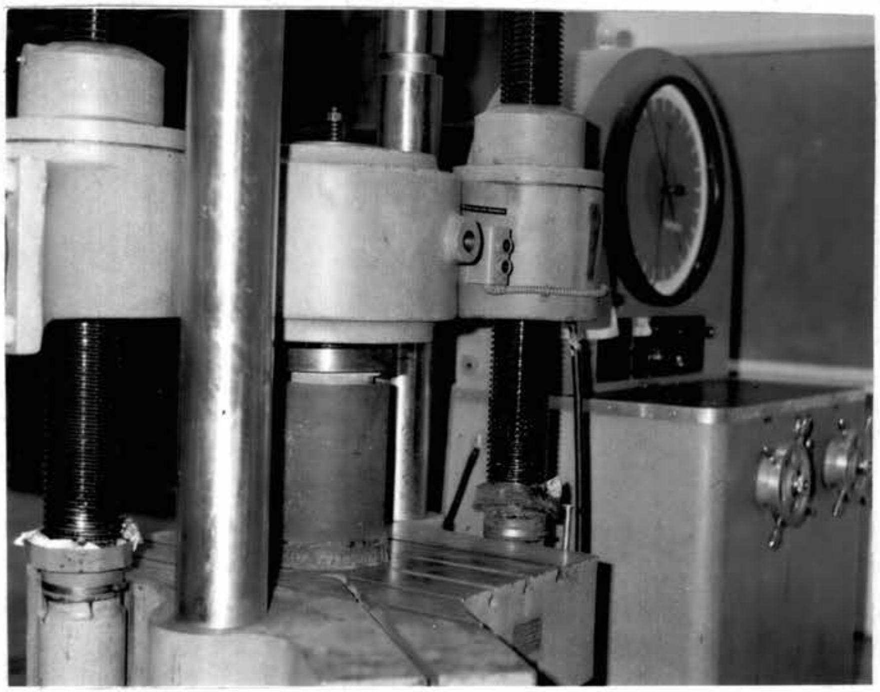

Figure 1. Baldwin, Tate, Emery, Universal Testing Machine Capable of Automatic Slow Cycling

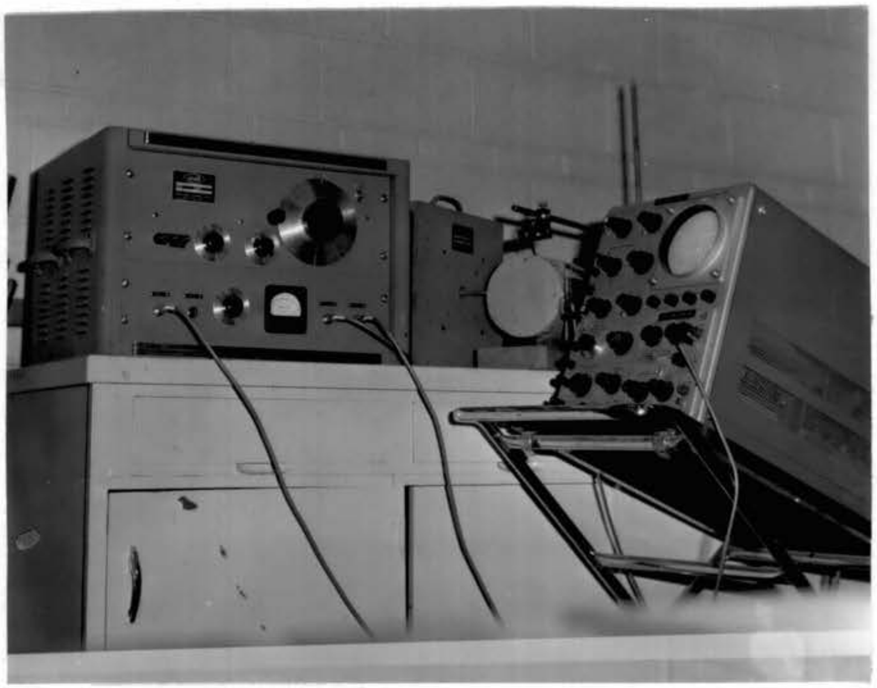

Figure 2. Sonic Modulus Equipment for Determining Dynamic Young's Modulus of Elasticity

6. Rotary polishing machine with coarse, medium and fine grinding powder.

7. Microscope having camera attachment with magnification from 50 to 00X.

8. Concrete coring machine.

9. Steel cylinder molds with steel base plates. An exception was made when waxed cardboard molds were used for a group of specimens cast together in a unit 4 ft. by 4 ft. by 12 in. deep and cured outside the laboratory (23).

3.6 Procedure

Before starting the slow cycle fatigue test both laboratory and core samples from the field were capped, then several specimens from each group were tested to establish the static compressive strength of the concrete. A third specimen from the same group was removed from the water tank and the dynamic modulus of elasticity was determined as shown in Figure 2. The specimen was then placed in a steel cylindrical tank with a milled base plate as shown in Figure 3. The cycle load was applied to the specimen by the universal testing machine while maintaining complete saturation in the apparatus as shown in Figure 1.

The cycle load was compressive and the peak load ranged from 35 to 90 percent of the average ultimate compressive stress previously determined on different samples. The most common cyclic load went from 0 to 70 percent and back to 0, each cycle. However, a number of other cyclic load patterns were used.

At periodic intervals during the test, the specimen was removed from the cyclic load machine and the dynamic modulus of elasticity was

Figure 3. Special Apparatus Used to Maintain Complete Saturation During Slow Cycle Fatigue Testing

determined. It was also necessary to frequently clean and lubricate the spherical head in order to insure free movement and to eliminate any bending in the specimens.

An automatic counter maintained a constant recording of the total number of load cycles.

Plots of the dynamic modulus vs. the number of load cycles were prepared from the data obtained. See Figures 4 through 9. The total number of load cycles to cause failure were compared for similar specimens from the same batch of concrete.

A microscopic study of the concrete specimens was made of polished samples cut from the specimens. For core specimens the samples cut from the ends prior to capping were polished and observed in the microscope. After careful study and detailed examination, any cracks found were marked for identification and photographed. The magnification used was from 50 to 200X.

In an attempt to correlate the extent of internal damage with the number of load cycles, samples for microscopic study were prepared from test specimens which had been subjected to increasing numbers of load cycles. For example, two specimens from the same source and each subjected to early freezing showed significant decrease in dynamic modulus at 2400 and 3600 cycles, respectively. The change in dynamic modulus was from 5.7×10^6 psi to 5.1×10^6 psi at 2400 cycles for the first sample and from 5.8×10^6 psi to 4.5×10^6 psi at 3600 cycles for the second sample. Samples for microscopic study from each specimen were prepared and comparisons made.

The dynamic modulus of elasticity was determined prior to the cyclic load test and at frequent intervals during the test to ensure

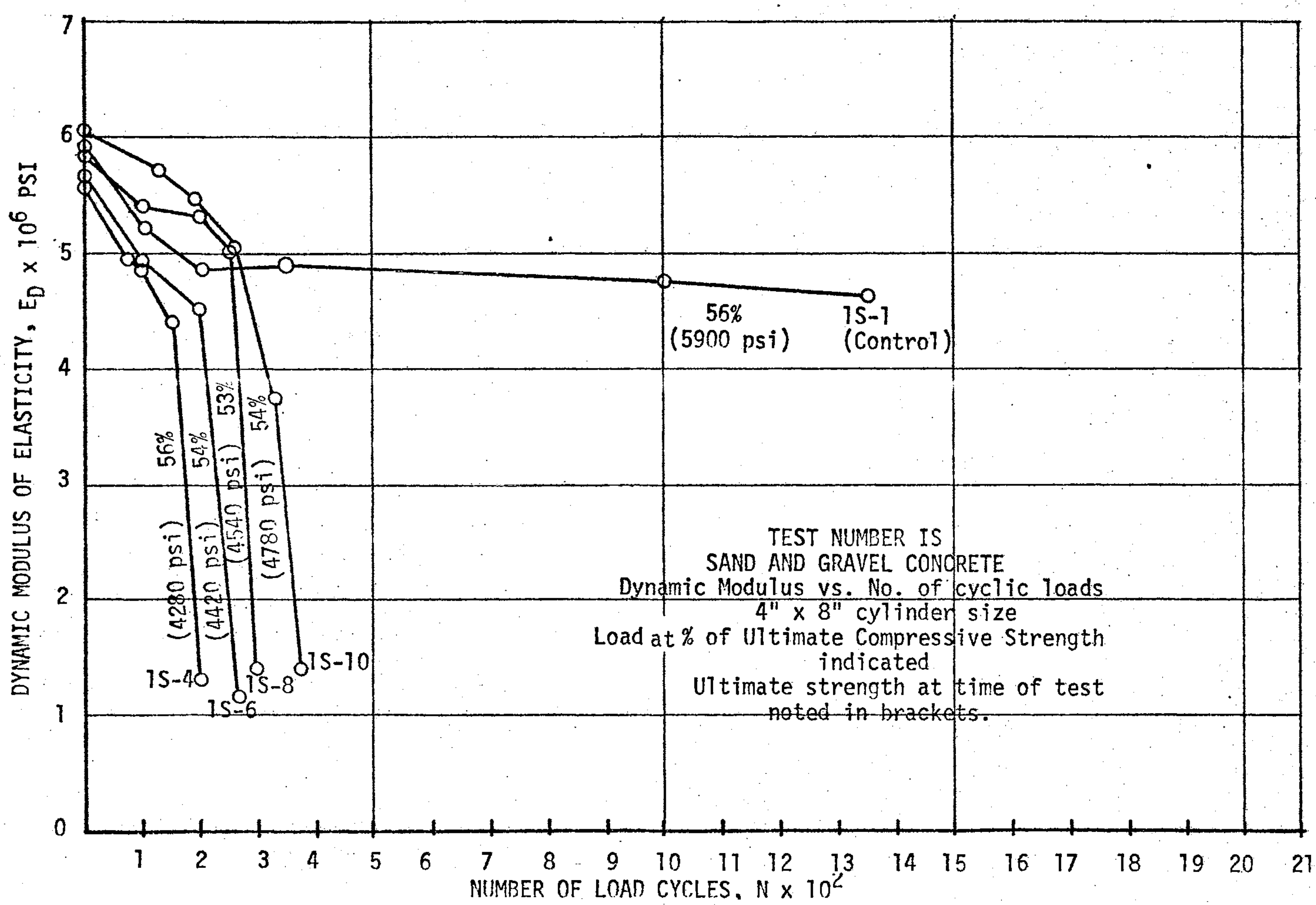

Figure 4. Dynamic Modulus of Elasticity vs. Number of Load Cycles

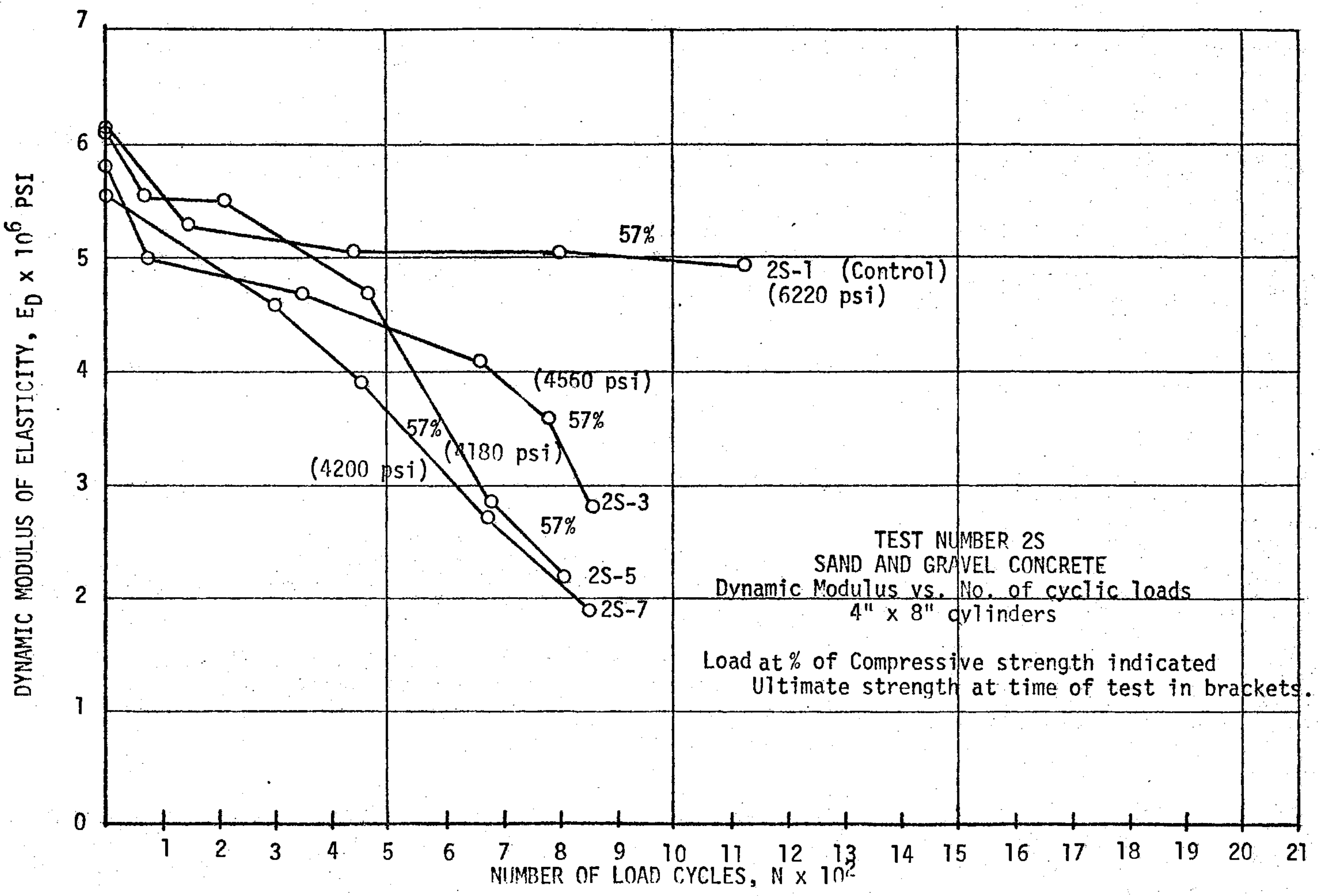

Figure 5. Dynamic Modulus of Elasticity vs. Number of Load Cycles

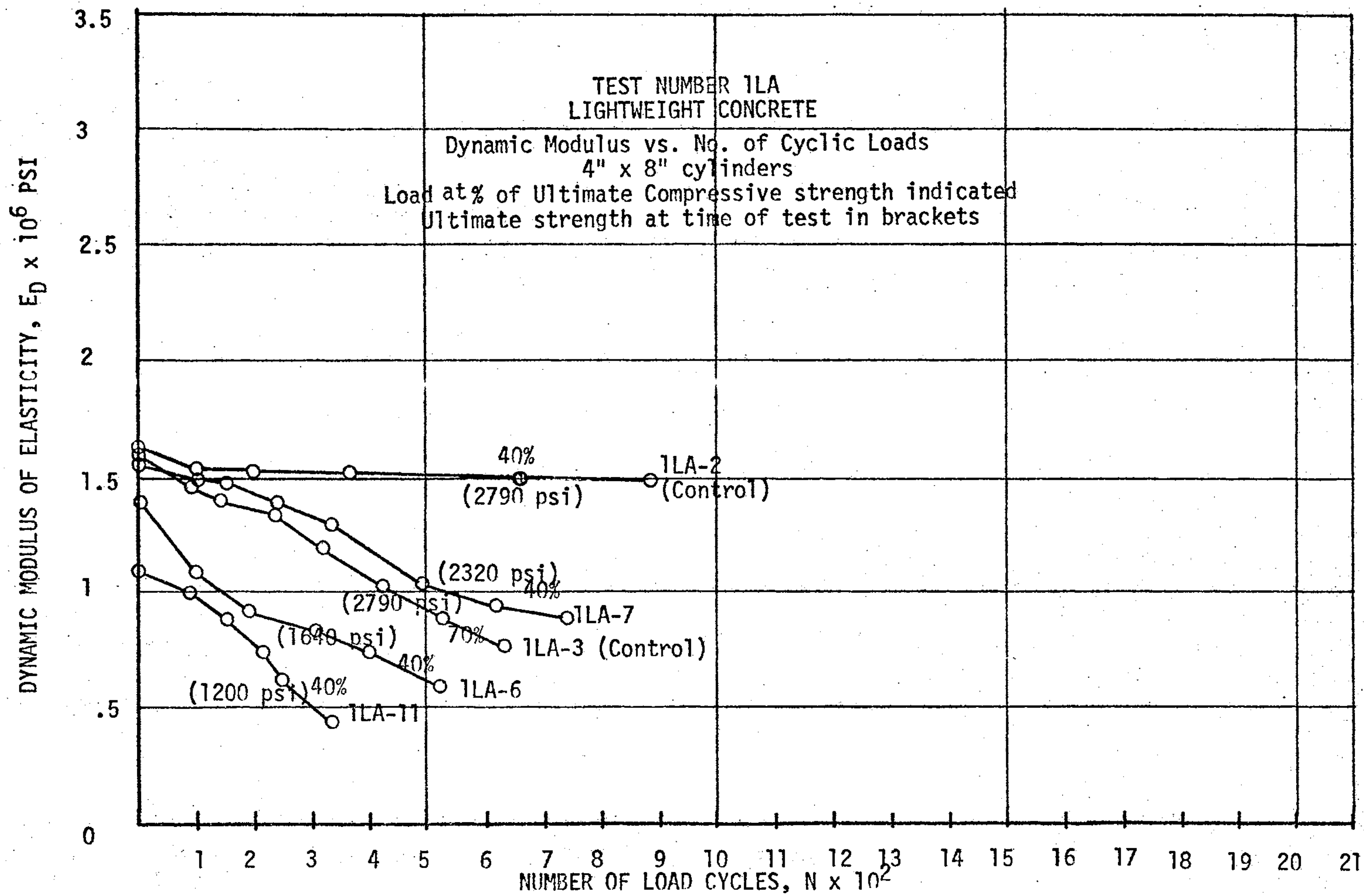

Figure 6. Dynamic Modulus of Elasticity vs. Number of Load Cycles

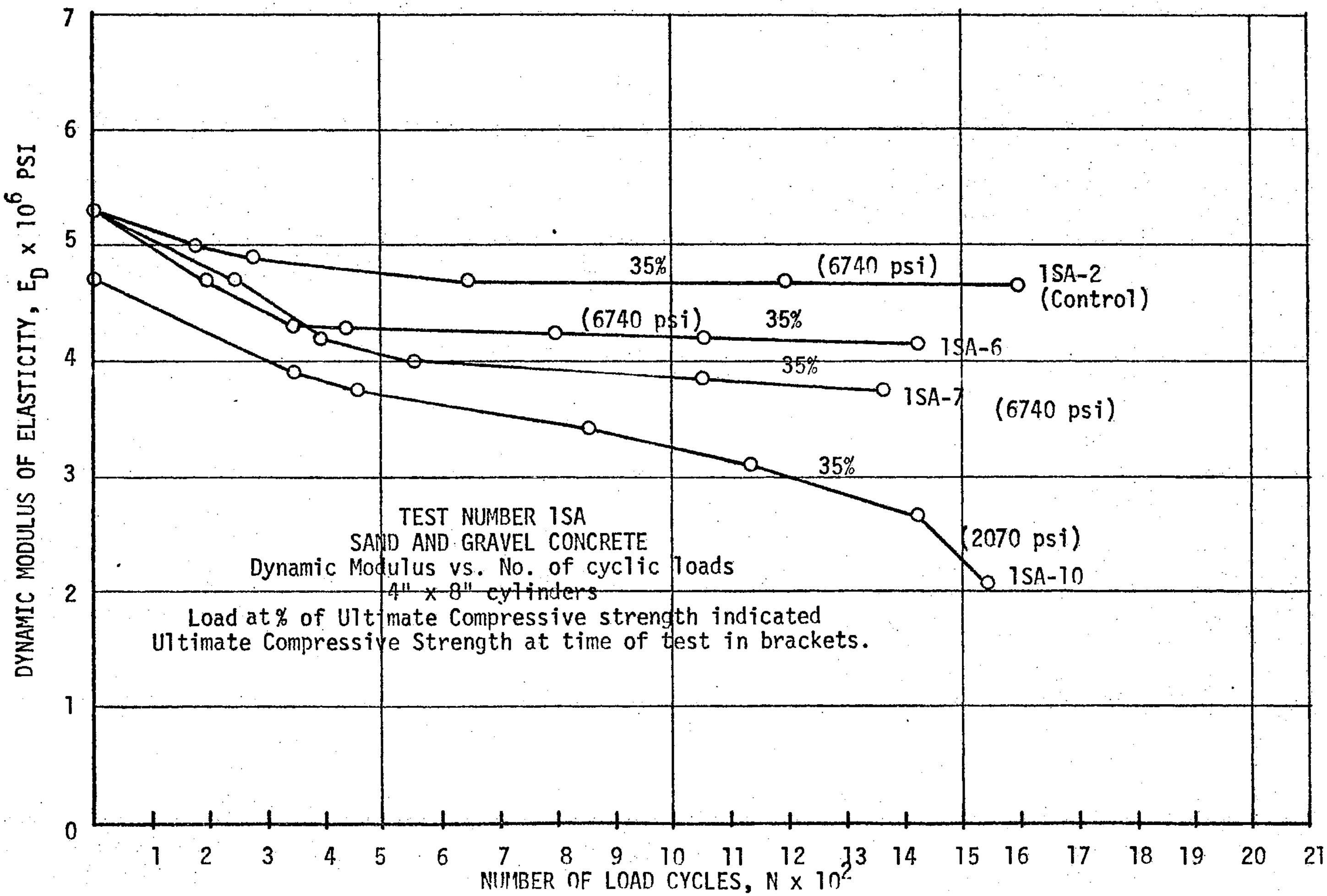

Figure 7. Dynamic Modulus of Elasticity vs. Number of Load Cycles

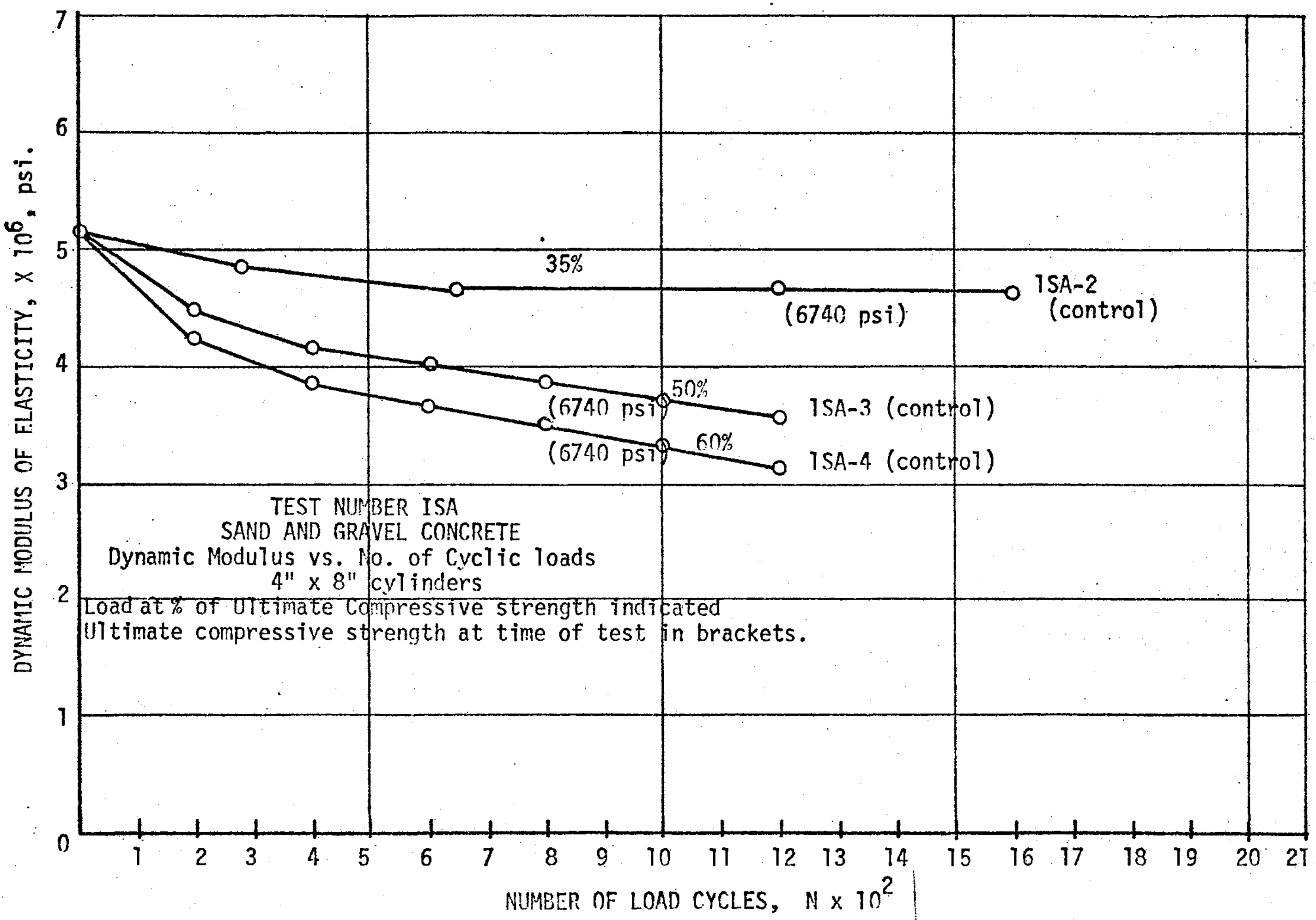

Figure 8. Dynamic Modulus of Elasticity vs. Number of Load Cycles

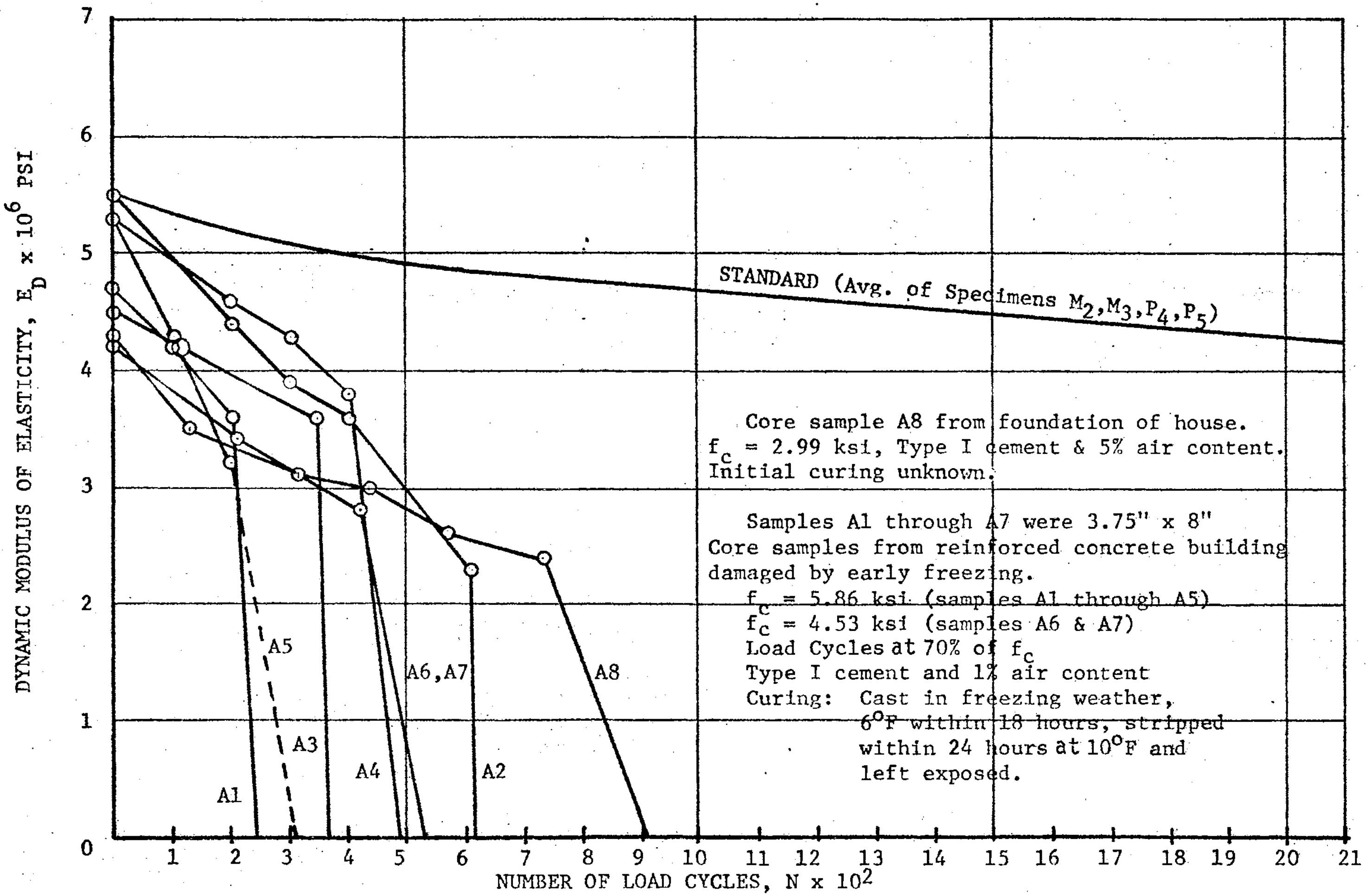

Figure 9. Dynamic Modulus of Elasticity vs. Number of Load Cycles. Field Conditions vs. Standard Conditions. Data From Tables II and VI.

sufficient data for calculating the durability factor and plotting the dynamic modulus vs. the number of load cycles. For example calculations refer to Appendixes A and B. The results of these tests are reported in the following chapter.

CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Slow Cycle Fatigue Method of Test

The slow cycle fatigue method of test developed during this research has provided a successful means for comparing the fatigue durability effects of freezing fresh concrete.

The method is briefly outlined:

(a) Concrete specimens: For convenience the specimens can be 4 by 8 in. or 6 by 12 in. cylinders. These are standard sizes for compressive strength specimens.

(b) Testing machine: The frequency of cyclic load is such that most compressive testing machines or universal testing machines can be operated without danger of damage to the machine. For this research a hydraulic universal testing machine was altered to cycle automatically and record the cycles for a total cost less than $200.

(c) Procedure: Concrete specimens, capped as normal compression test specimens, were saturated 48 hours prior to the cyclic load application. The specimens were placed in the sonic test equipment and the dynamic modulus of elasticity determined. The specimen was transferred to the testing machine for cyclic load. Since the test must be conducted on the specimen in a saturated condition, a steel cylindrical tank was used to maintain saturation during the test.

If the peak cyclic load is 70 percent of the ultimate compressive strength and varies from zero load, the cyclic load portion of the test can usually be completed in two days. In the reported tests the ultimate compressive strength was obtained from additional specimens from the same source immediately preceding the cyclic load test.

At frequent intervals the test was stopped, the sample removed, and the dynamic modulus of elasticity determined.

A durability factor was calculated, both a plot of dynamic modulus of elasticity vs. number of load cycles, and the number of cycles of load to cause complete failure were compared as a measure of fatigue durability.

For the purposes of this research, good or poor fatigue durability is a relative measure of how concrete resists cyclic loads. A definite quantity or number is not available to indicate a particular level of durability. Only when comparisons are made between similar concrete samples subject to different curing and cyclic loading conditions as outlined in this research, can a realistic comparison be made. Even then further research should be performed before adequate correlation can be obtained between the results of the suggested test procedure and field conditions.

4.2 Durability of Concrete Specimens

Figures 4, 5, 6, 7, 8, and 9 graphically represent the influence of freezing of fresh concrete on its response to slow cycle fatigue testing. In these figures, there was a significant change in the number of cycles-to-failure for specimens damaged as compared to those not damaged by early freezing. Except for Figure 8 each figure represents a group of specimens from the same concrete batch but subject to different curing conditions during the first 48 hours. Control specimens refer to standard cured specimens while the remaining specimens were all subject to early freezing. For specific properties and curing conditions, refer to Appendix C.

Figure 9 is a graphical representation of change in fatigue durability for concrete core specimens taken from actual structures. Except for specimen A8, which had unknown curing conditions, the remaining specimens A1 through A7 were subject to freezing temperatures during the initial 24 hour curing period. Note the marked similarity between the laboratory specimens of Figure 4 and the core specimens of Figure 9.

4.3 Bond Failure Effect of Early Freezing

After concrete specimens were subjected to freezing temperatures while the concrete was still plastic, the microscopic examination revealed flaws around the coarse aggregate particles. These flaws at the coarse aggregate interface increased in number and size with the number of load cycles until a complete breakdown of the specimen resulted.

Figure 10 is typical of specimens cured under standard conditions while Figures 11, 12, and 13 are representative of specimens which were subject to freezing temperatures during the initial cure period.

The progressive breakdown of damaged specimens is represented in Figures 14 and 15. Observe the clean separation of the coarse aggregate from the cement matrix as a result of a weak bond relationship.

A study of samples from the core specimens which had been taken from a structure exposed to freezing during the initial curing period indicated that bond cracks were present and easily identified. Figures

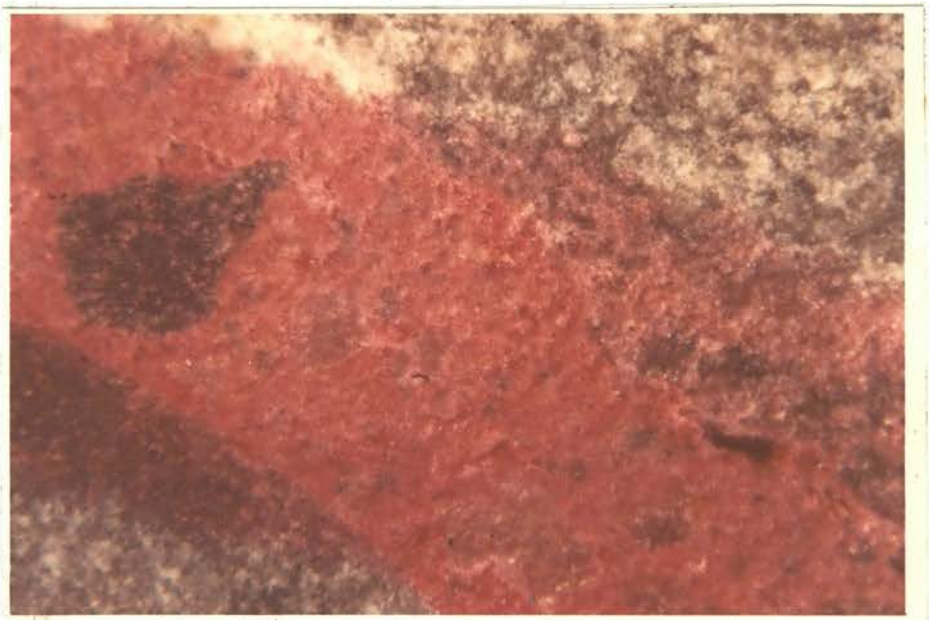

Figure 10. Microscopic Study of Aggregate Matrix Interface of Sample M3 After 3600 Cycles at 70% of Ultimate Load. No Cracks Typical for Non-Damaged Specimen. Magnification is 51x.

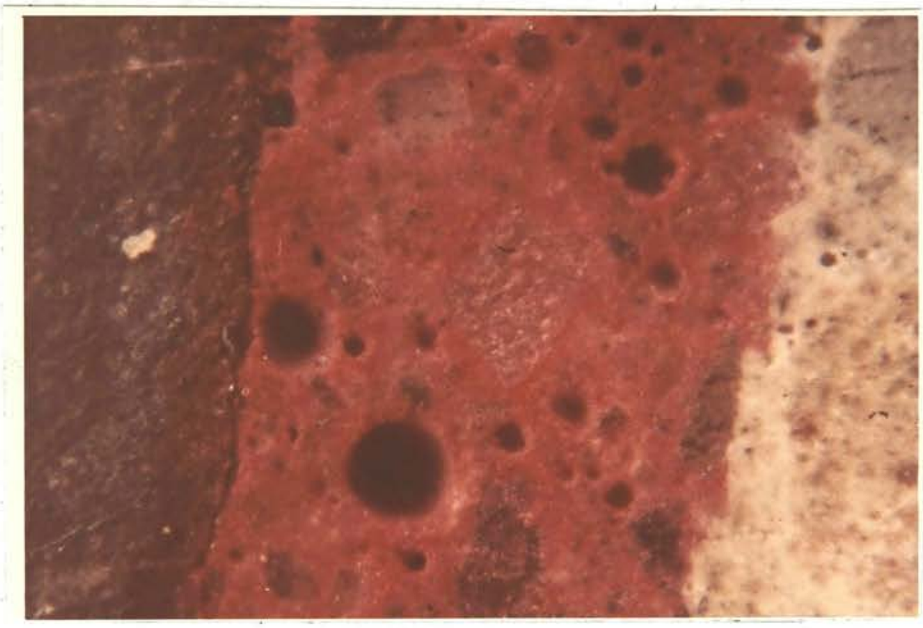

Figure 11. Microscopic Study of Aggregate Matrix Interface of Sample FP6 After 818 Cycles at 70% of Ultimate Load. Typical Bond Crack Clearly Visible for Damaged Specimen. Magnification is 51x

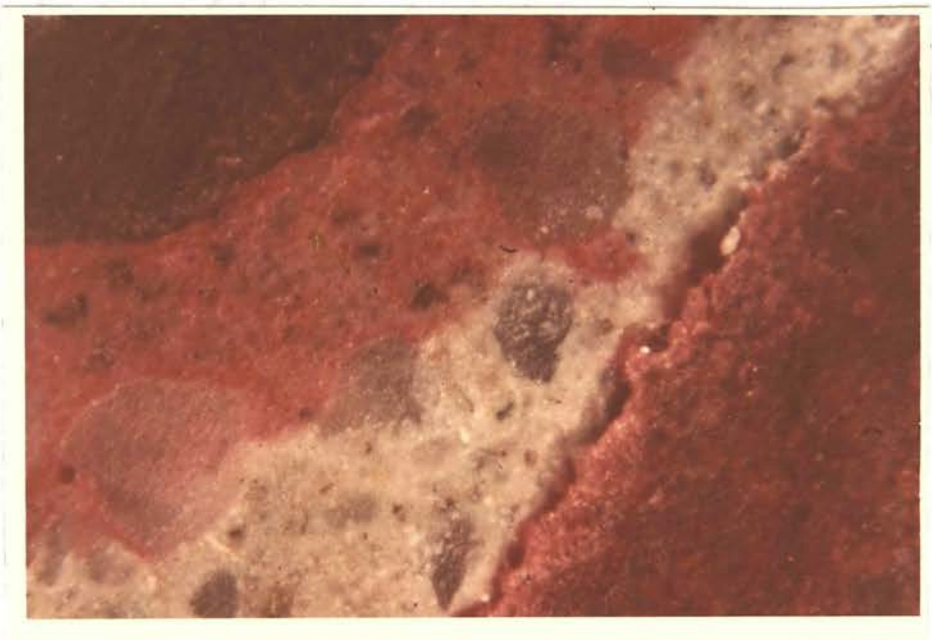

Figure 12. Aggregate Bond Crack on Core Sample Similar to Samples A1, A2, A3. Damage was Done Eight Years Prior to Photograph. Magnification is 51x

Figure 13. Aggregate Bond Crack and Matrix Crack on Core Sample Similar to A1, A2, A3. Damage was Done Eight Years Prior to Photograph. Magnification is 51x

Figure 14. Progressive Bond Failure for Core Sample A5. Typical of Damaged Specimens

Figure 15. Ultimate Failure of Core Sample A3 Indicating a Bond Failure Around the Aggregates. Typical of Damaged Specimens

12 and 13 show typical bond cracks existing after eight years of service even though the concrete had increased in average strength from 3000 psi to 5855 psi.

4.4 Effects of Air Entrainment

Air-entrained specimens appeared to be affected to a lesser degree by freezing temperatures, early in the curing period, than non-air-entrained specimens. Doshi (28) found that the durability factor of both standard specimens and those subject to early freezing varied as the percent of entrained air varied. The greatest durability factor occurred at five percent entrained air for 3/4 in. maximum size aggregate. See Figure 16.

4.5 Relationship Between Compressive Strength and Durability

One of the most significant results of the tests was in the lack of correlation found between compressive strength and fatigue durability in specimens that have been frozen. Concrete with compressive strengths ranging from 2500 psi to more than 6000 psi are in common use throughout the building industry. For example, the concrete strengths in excess of 4000 psi shown in Figures 4 and 5 and the concrete strengths in excess of 5800 psi shown in Figure 9 would under normal conditions be considered excellent. <u>However, concrete specimens with sufficient strength to meet the structural and building code requirements may exhibit poor fatigue durability (as seen in Figures 4, 5, 6 and 9) if the concrete had been subjected to freezing temperatures soon after placing.</u>

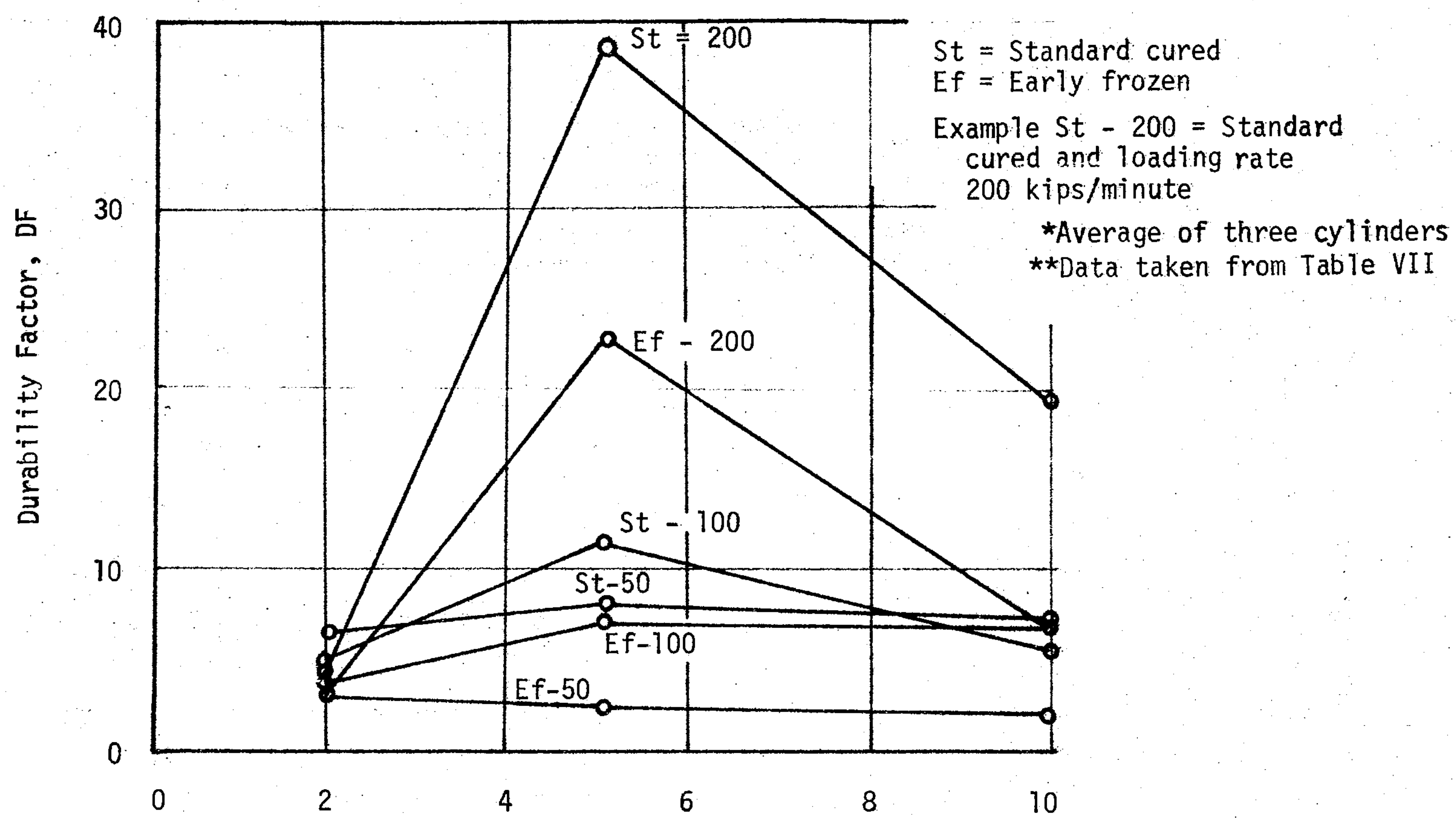

Figure 16. Air Content vs. Durability Factor (20)

4.6 Statistical Evaluation

Applying statistical techniques to the experimental data from Doshi (28) which are found in Table VII, a significant difference is found between specimens cured in a standard manner and those subject to early freezing.

Table I indicates the results of 6 by 12 in. cylindrical specimens which were placed in the freezer units in limited numbers to insure freezing temperatures throughout the initial curing period. The air content was varied and the rate of load was varied for both standard cured specimens and those frozen after only six hours of air curing. Comparisons of durability factor, number of cycles to failure and compressive strengths are made for specimens originally cast from the same batch of concrete.

Statistically, using the t-distribution with a level of significance equal to 0.05, the results are as follows:

1. The durability factor for frozen samples was significantly lower than for the unfrozen samples;

2. The number of cycles to failure was significantly lower for frozen samples; and

3. The compressive strength was significantly lower for frozen samples.

If we consider the average percent change in the above comparisons for the frozen samples, they become (1) for the durability a decrease of 47.4%; (2) for the number of cycles to failure a decrease of 38.1%; (3) for compressive strength a decrease of 4.5%.

TABLE I

RESULTS OF CYCLIC LOAD TESTS (6 INCH X 12 INCH CYLINDERS)(28)

Group	Number of Specimen	Percent Air Content	Average Compressive Stress ksi	Percent Decrease From Standard	Curing Period Days	Rate of Cyclic Load Kips per Minute	Average Cycles to Failure	Percent Decrease From Standard	Average Dynamic Modulus $E_D \times 10^3$ ksi	Average Durability Factor DF	Percent Decrease From Standard
A_{St}	3	2	4.16	7.0	38	200	782	68	5.51	4.12	23
A_{Ef}	3		3.87		44		248		5.35	3.17	
B_{St}	4	2	4.32	5.8	83	100	412	46	5.42	5.27	37
B_{Ef}	4		4.07		86		219		5.42	3.28	
C_{St}	3	2	4.46	1.6	45	50	221	8	5.48	6.32	56
C_{Ef}	2		4.39		54		203		5.14	2.78	
D_{St}	3	5	3.75	4.5	76	200	1240	23	4.82	39.11	42
D_{Ef}	3		3.58		79		943		4.87	22.65	
E_{St}	3	5	3.69	6.2	76	100	920	28	5.44	11.61	40
E_{Ef}	3		3.46		79		655		5.38	6.92	
F_{St}	3	5	3.66	13.7	75	50	375	38	5.25	8.09	70
F_{Ef}	3		3.16		79		229		5.32	2.41	
G_{St}	4	10	3.85	3.1	88	200	722	57	4.92	19.13	64
G_{Ef}	4		3.73		80		304		4.96	6.88	
H_{St}	3	10	4.64	2.4	78	100	458	12	4.91	5.65	22
H_{Ef}	3		4.53		83		402		5.14	4.38	
I_{St}	4	10	4.25	3.5	77	50	429	63	4.72	7.69	73
I_{Ef}	4		4.40		83		158		4.74	2.07	

St = standard cured

Ef = early frozen

CHAPTER V

DISCUSSION

5.1 General

Testing of specimens for this research was done over a period of several years. Even though all of the cement for the laboratory came from the same source* it was obtained at the beginning of each phase of the research. Thus the purchase of the cement as well as the sample preparation and testing was extended over a period of serveral years.

Difficulty in obtaining consistent results was observed when specimens which were several days old were subject to slow cycle fatigue testing. For example, at seven days concrete is still gaining strength rapidly under moist curing. It was observed that during the testing time the compressive strength increased and hence the percent of load and rate of loading decreased enough to influence the results. For example, the fatigue test for specimen FC19 was commenced with a cyclic load that varied from a peak value of 70 percent to a minimum value of 35 percent of the average ultimate compressive strength. After 1800 cycles the average ultimate compressive strength was again checked by using reserve specimens, and the compressive strength was found to have

---

*Ideal Cement Company, Devils Slide, Utah.

increased. The actual loading condition at the end of 1800 cycles ranged from 60 percent peak load to 30 percent minimum cyclic loading (21,22).

Variations were observed in the amount and depth of damage caused by early freezing. The number and size of specimens in addition to the type and amount of cement used in the specimens were variables that seriously affected the degree of damage caused by a laboratory freezer of limited heat exchange capability. In some cases the temperature rose and remained above freezing for as much as four hours after introduction of specimens to the freezer cabinet. Since the extent of damage was dependent in part upon the strength of the concrete prior to the time of freezing, it became necessary to limit the quantity of concrete placed in a freezer unit at one time.

For example, the following results taken from Tables II and III (21, 22, 24, 25, 26, 27) indicate that concrete samples when subject to freezing conditions in a laboratory environment may produce sufficient heat due to hydration to keep the major portion of the concrete above freezing. The resulting cool curing can result in an increased compressive strength if standard curing is later continued. However, a reduction in the durability factor and the number of cycles-to-failure can still occur.

	Standard	Early Freezing
Average Durability Factor	19.2	15.2
Average Compressive Strength	6,380 psi	6,460 psi
Total Number Specimens	30	25
Average Cycles to Failure	1,079	851

TABLE II

DURABILITY OF CONCRETE SAMPLES SUBJECT TO CYCLIC LOADING
AND STANDARD CURING CONDITIONS

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF[b]	Cycles to Failure
M1	90	1	7.50	64	124.20	5.6	89.3	8070
M2, M3	28	1	6.86	70	135.71	5.7	86.0	3000+
P4, P5	28	5	5.15	70	102.14	5.3	64.2	2307
P6	120	9	5.01	70	99.34	4.6	25.3	1421
V7	15	1	5.94	35 + 35	58.84	5.4	82.8	1800+
V8, V9	16	1	6.00	70	118.37	5.3	13.3	513
V10	17	1	6.01	35 + 35	59.50	5.4	83.2	1800+
C11	30	1	6.25	70	123.90	5.6	41.1	1699
V12, V14	14	5	4.93	70	97.56	4.6	17.2	592
V13	14	5	4.93	35 + 35	48.78	5.0	81.5	1820+
V15, V16	14	5	5.00	35 + 35	49.53	5.0	75.6	1919
D17, D18, D19	33	1	6.77	70	200.00	5.6	26.7	893
D20, D21, D22	33	5	6.16	70	200.00	5.5	12.3	559
D23, D24, D25	37	8	5.00	70	200.00	4.6	10.5	579
D26, D27, D28	62	10	5.56	70	200.00	5.1	12.1	564
D29, D30, D31	66	6.5	6.25	70	300.00	5.3	13.6	756
L32, L33, L34	69	5	7.02	70	200.00	5.9	15.3	1076
L35,[c] L36[c]	92	1	7.42	70	200.00			850
L37, L38, L39	51	5	6.26	70	200.00	5.5	34.9	1224
L40, L41	41	1	7.17	70	200.00	5.5	10.1	690
L42, L43, L44	87	5	5.65	70	200.00	4.9	16.2	622
L45, L46, L47	84	1	7.91	70	200.00	6.1	15.5	709
L48, L49, L50[d]	55	5	5.84	70	200.00	4.9	8.1	482
L51, L52	73	1	7.30	70	200.00	4.7	51.6	5520

TABLE II (Continued

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF[b]	Cycles to Failure
1S-1	28	1	5.90	56	41.6	--	--	--
2S-1	28	1	6.22	57	44.6	--	--	--
1LA-2	28	9	2.79	40	14.1	--	--	--
1LA-3	28	9	2.79	70	24.6	--	--	--
1SA-2	28	5	6.74	35	29.7	--	--	--
1SA-3	28	5	6.74	50	42.5	--	--	--
1SA-4	28	5	6.74	60	63.6	--	--	--

[a]70% cyclic load means 70% of the ultimate compressive strength was applied as a cyclic load. 35 + 35 means 35% of ultimate strength as static load and 35% as cyclic load.

[b]Relative measure of durability. High DF, good durability; low DF, poor durability.

[c]Sonic Modulus Equipment was not operating properly.

[d]Probably error in results.

TABLE III

DURABILITY OF CONCRETE SAMPLES SUBJECT TO CYCLIC LOADING
AND EARLY FREEZING CONDITIONS

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF[b]	Cycles to Failure
FM1	90	1	7.45	70	147.00	5.6	17.8	1438
FM2, FM3	28	1	6.43	70	127.34	5.6	6.5	175+
FP4, FP5, FP6	28	5	5.07	70	100.40	5.2	37.6	1504
FP7, FP8	120	9	4.90	70	96.83	4.7	19.6	948
FV9, FV10	15	1	5.64	70	111.70	5.2	4.9	138
FV11, FV12	15	1	5.77	35 + 35	57.15	5.2	32.7	1158
FV13, FV14	27	5	4.71	70	93.20	4.4	14.0	328
FV15	26	5	5.43	35 + 35	107.60	4.9	52.8	1441
FV16	15	5	4.65	35 + 35	91.80	4.4	40.0	1401
FC17	8	5	4.31	40 + 40	48.63	3.3	.3	55
FC18	8	5	4.31	80	97.26	3.3	4.8	190
FC19	7	5	4.04	35 + 35	40.00	3.3	86.5	1800+
FC20	27	5	4.87	35 + 35	48.16	4.6	43.8	1315
FC21	27	5	4.87	30 + 30	41.28	4.6	92.2	1800+
FC22	7	1	4.34	80	98.26	4.7	4.8	115
FC23	7	1	4.34	60	73.70	4.6	8.4	1437
FC24	6	1	5.45	40 + 40	61.73	4.2	4.4	116
FC25, FC26	8	1	5.78	45 + 45	73.70	3.4	.6	34
FC27	27	1	6.41	70	126.98	5.5	14.9	1206
FC28	27	1	5.21	66	97.50	4.4	9.4	1187
FC29	31	1	5.64	60	95.70	5.6	88.0	1800+
FC30	31	1	5.64	62	98.89	5.4	62.0	1800+
FC31	28	1	6.27	40 + 40	70.90	5.5	3.3	79

TABLE III (Continued)

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF[b]	Cycles to Failure
FC32	28	1	6.27	35 + 35	62.00	5.5	28.3	1115
FC33	25	1	6.32	30 + 30	53.58	5.5	90.5	1800+
FC34	25	1	6.32	35 + 35	62.51	5.4	49.9	1218
FC35	30	1	6.80	34 + 34	65.45	5.7	90.1	1800+
FC36	30	1	6.80	35 + 35	67.38	5.7	89.4	1800+
FC37	27	1	6.27	35 + 35	62.13	5.4	70.2	1745
FC38	27	1	6.27	40 + 40	71.00	5.5	13.3	354
FC39	27	1	6.27	35 + 35	62.13	5.6	35.1	1151
FD41[c]	34	1	6.80	70	200.00	5.4	.6	128
FD40, FD42	34	1	6.80	70	200.00	5.6	21.0	1480
FD43, FD44, FD45	35	5	6.94	70	200.00	5.5	14.7	594
FD46, FD47, FD48	38	8	4.98	70	200.00	4.8	15.5	745
FD49, FD50, FD51	67	10	5.80	70	200.00	5.0	13.6	586
FD52, FD53, FD54	72	6.5	6.64	70	300.00	5.3	18.5	810
FD58, FD59, FD60	98	6.5	7.21	70	50.00	5.7	2.9	212
FL61,[d] FL62[d]	72	5	8.16	70	200.00			617
FL63,[d] FL64,[d] FL65[d]	83	1	7.99	70	200.00			1157
FL66, FL67, FL68	48	5	7.39	66	200.00	5.6	17.6	842
FL69, FL70, FL71	46	1	8.00	70	200.00	5.8	49.0	1665
FL72,[d] FL73, FL74	90	5	5.81	70	200.00	4.8	15.5	573
FL75, FL76,[d] FL77	83	1	6.63	70	200.00	5.7	5.4	451
FL78, FL79, FL80	57	5	6.04	70	200.00	4.9	13.7	997
FL81, FL82, FL83	69	1	7.57	70	200.00	5.8	23.0	1639

TABLE III (Continued)

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF[b]	Cycles to Failure
1S-4	28	1	4.28	56	30.2	--	--	200[e]
1S-6	28	1	4.42	54	30.1	--	--	275[e]
1S-8	28	1	4.54	53	30.2	--	--	300[e]
1S-10	28	1	4.78	54	32.5	--	--	375[e]
2S-3	28	1	4.56	57	32.8	--	--	850[e]
2S-5	28	1	4.18	57	30.0	--	--	
2S-7	28	1	4.20	57	30.1	--	--	850[e]
1LA-6	28	9	1.64	40	8.27	--	--	550[e]
1LA-7	28	9	2.32	40	11.67	--	--	750[e]
1LA-11	28	9	1.20	40	6.05	--	--	350[e]
1SA-6	28	5	6.74	35	29.7	--	--	
1SA-7	28	5	6.74	35	29.7	--	--	
1SA-10	28	5	2.07	35	9.1	--	--	1550[e]
1SA-12	28	5	5.25	35	23.2	--	--	

[a]70% cyclic load means 70% of the ultimate compressive strength was applied as a cyclic load. 35 + 35 means 35% of ultimate strength as static load and 35% as cyclic load.

[b]Relative measure of durability. High DF, good durability; low DF, poor durability.

[c]Unexpected failure. Results not considered reliable.

[d]Sonic modulus equipment was not operating properly.

[e]Approximate values.

The above specimens were each 6 by 12 inch cyclinders tested at a cyclic load of 70 percent of the ultimate compressive strength. The loading rate was 200 kips per minute. The 25 specimens subject to early freezing were originally part of the same batches as the 30 standard specimens. The only difference was in curing during the first 24 hours. It should be noted generally that a decrease in compressive strength was observed if the specimen actually froze throughout rather than freezing superficial on the surface during initial cure period. If 20 matched pairs are considered statistically using the t-distribution with the level of significance equal to 0.05, there exists a significant increase in compressive strength for the cool cured samples with no significant change in durability factor or the number of cycles to failure.

All specimens associated with Table VII (28) were placed in the freezer units in fewer numbers to reduce the above mentioned problem. As seen from the results in Table VII, with one exception, all specimens subject to early freezing had a corresponding reduction in ultimate compressive strength. The durability factor and number of cycles to failure were consistently less for all specimens subject to early freezing.

Even though a durability factor can be calculated, insufficient information is available to verify that a particular number represents good fatigue durability or not. Durability factors range between 0 and 100. A high durability factor represents good fatigue durability and a low durability factor represents poor fatigue durability. However, the durability factor is a relative measure of fatigue durability and is most effective when comparing concrete of questionable quality vs.

concrete of good quality from the same source. Additional study and evaluation of the durability factor may eventually provide a general range, below which would be classed as questionable concrete and above as good concrete relating to fatigue durability, but as yet this is not possible.

Results from early investigations indicated that as a sample dried out the number of cycles to failure increased greatly (19, 20). Therefore, to insure a consistent and practical means of control, the specimens were tested in a saturated condition in a special apparatus shown in Figure 3. A milled steel base plate was inserted in the bottom of the special apparatus to insure an even distribution of load on the specimen.

Since the rate of loading influences the number of cycles to failure for a specimen, it was necessary to periodically check the rate and make any necessary adjustments.

Cracks were observed in specimens which had been subject to early freezing. The cracks were observed adjacent to and around the coarse aggregates and were usually observed on the same side of the aggregates. The position and nature of the cracks appeared to be associated with the bleeding process, where free water, while moving through the concrete, accumulated adjacent to the coarse aggregate in the direction of bleeding. This accumulated free water then froze, expanded and caused a crack which resulted in a bond failure between the cement paste and the coarse aggregate.

5.2 Supporting Data

Continuing research has added supporting data to the successful application of the slow cycle fatigue method of test (21, 22, 23, 24, 25, 26, 27, 28).

For the slow cycle type of test it was found that the rate of loading was directly proportional to the number of load cycles causing failure as shown in Figure 17 (28).

The total time required to complete a slow cycle fatigue test was nearly the same regardless of the rate at which the load was applied.

Type III portland cement with its increased heat of hydration and rate of strength gain offers some benefits for concrete subjected to freezing temperatures. The average durability factor and number of cycles-to-failure increased when type III cement was used instead of type I (20, 23). Figure 18 graphically shows the variation in durability factor affected by air entrainment and type of cement.

5.3 Field Testing

The slow cycle fatigue method of test can be applied in the field to an actual structure when damage resulting from the freezing of freshly placed concrete is suspected.

If a portion of a concrete structure is suspected of damage and a cycle test is anticipated, core specimens from the concrete can be subjected to cyclic loads and the results of; (a) durability factor, (b) changing dynamic modulus and (c) the number of cycles-to-failure can be determined. These results should then be compared to similar results from standard cured samples taken when the concrete was placed.

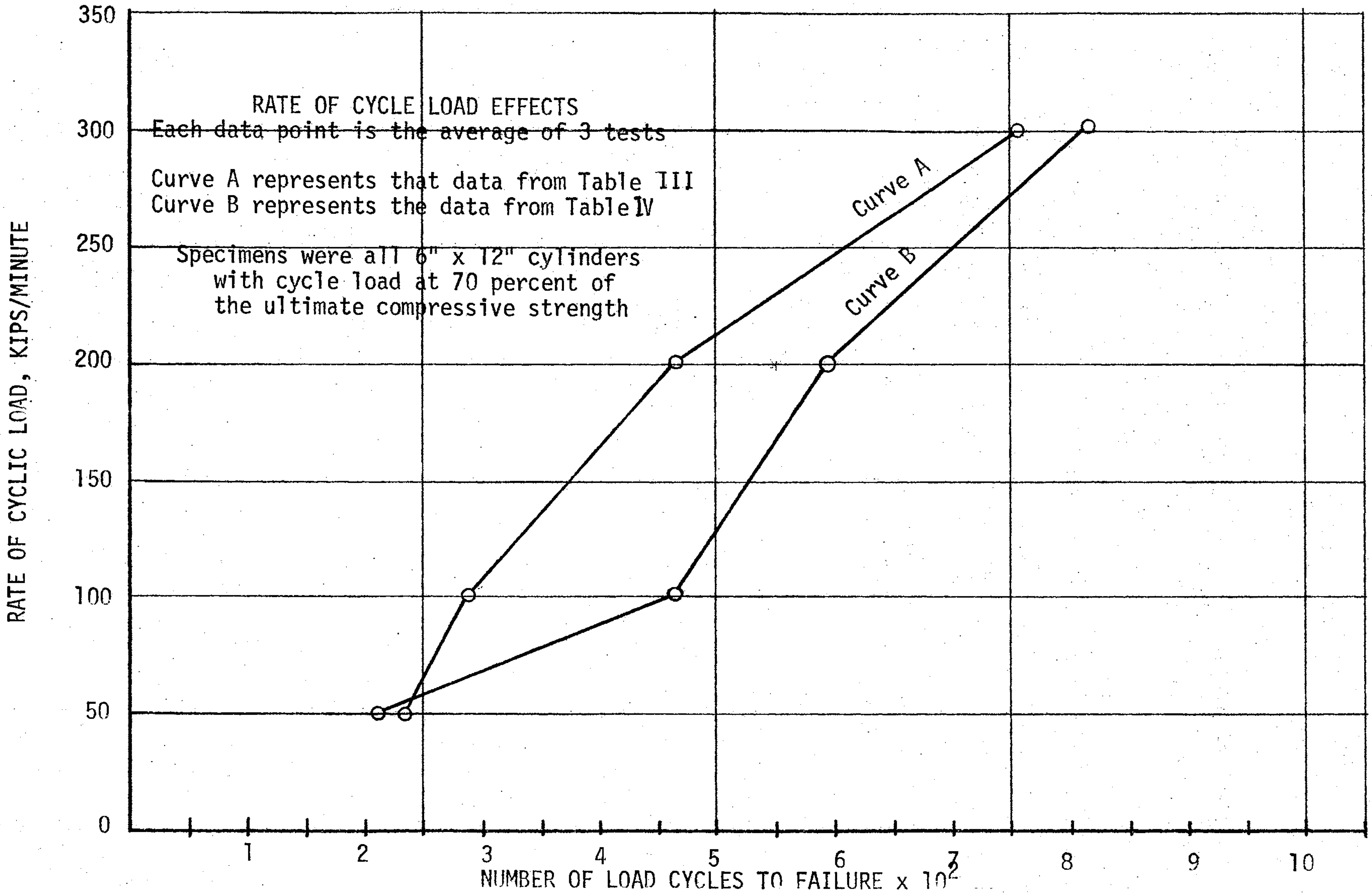

Figure 17. Rate of Cyclic Load, Kips/Minute vs. Number of Load Cycles

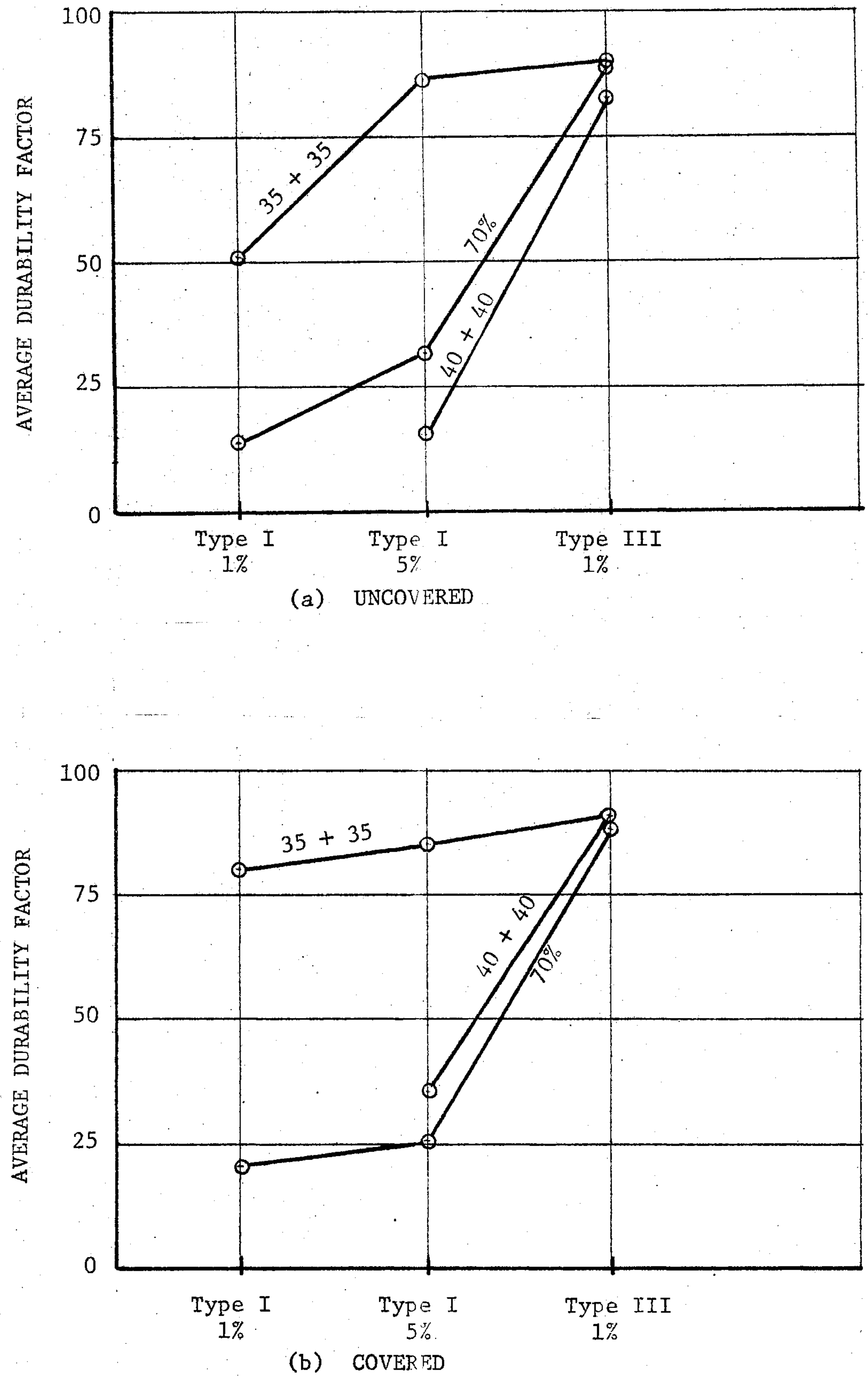

Figure 18. Durability Factor Varies With Load, Type Cement, and Entrained Air (Data From Table VI)

It is possible to take core specimens from areas not suspected of damage due to freezing and compare the results listed above with specimens taken from the suspected frozen area. Caution should be taken to complete all tests under similar conditions holding constant as many variables as possible.

A list of the variables that can have a significant effect on the results listed previously follow as a reminder and guide: (1) type of cement, (2) rate of loading, (3) size and shape of specimen, (4) use of additives such as entrained air, (5) age at time of test, (6) type and extent of curing, (7) moisture content of specimen at time of test, (8) extent of freezing, (9) compressive strength of specimen at time of freezing, (10) number of cycles of freezing and thawing, (11) amount of loading considered as a percent of the ultimate strength, and (12) mix design and type of materials used in the concrete.

When most of these variables listed above are held constant, the cycle load test will indicate a relative durability of the frozen concrete. A limitation on the practical application of such tests, however, is that several days would be required to obtain specimens and complete the cycle load test on suspected concrete. A microscopic study of concrete samples from the suspected area could, however, provide some visual evidence of damage due to freezing the fresh concrete.

5.4 Hypothesis Relating Static and Fatigue Properties

The order in which stress levels are applied to a material has an important effect on the progress of fatigue damage (52). For example, a coarse crack started by a previous high stress will not propagate very rapidly under a subsequent low stress. On the other hand, a fine crack left by a previous low stress might propagate very rapidly under a subsequent high stress. Applying this principle in the case of early freezing of concrete where bond cracks have been produced as a result of early freezing before any load is applied, it seems reasonable to assume that some of the bond cracks will be in such a direction as to propagate more rapidly than if the bond crack did not exist. This process in turn would cause the concrete to disintegrate more rapidly as illustrated in Figures 10 and 11, if it had been damaged by early freezing than would be indicated by static test.

Fatigue of a material is strongly influenced by minor as well as major discontinuities in structure. It is influenced by stress-concentrations and in general by the non-homogeneous nature of the material. If by some action a concrete structure is made less homogeneous or if discontinuities in the structure are present because of freezing action, then the fatigue life would be reduced.

Figures 12 and 13 show aggregate bond cracks in which the concrete was allowed to freeze before sufficient hydration and strength had occurred to prevent damage. When bleeding occurs in concrete, there is a tendency for this water to accumulate adjacent to large impervious objects such as aggregate, steel reinforcement, formwork, etc. If the concrete is exposed to freezing conditions at the time this bleeding is taking place the accumulated free water can freeze and form ice in these regions. The expansion caused by the ice formation results in extending any existing cracks adjacent to the hard objects as well as producing new cracks in the cement matrix. As a result, the fatigue durability of any concrete which is later subject to repeated loads will be less than if the concrete had not been allowed to freeze.

Concrete which has been frozen may however, under continued moist curing conditions, attain suitable compressive strength. The compressive strength could be well above minimum structural requirements, as illustrated in the accompanying tables. The load under static conditions can be transferred by a three dimensional shell or structural action past the large aggregate around which the bond has been destroyed. Thus a static compressive test will not indicate the presence of or effect of the decreased bond on the aggregate. A fatigue loading however, will cause some of the bond cracks to enlarge and extend, altering the fatigue durability of the concrete as well as the fatigue durability of concrete structures.

A similarity exists between static compressive strength test and a fatigue type test. Both tests result in failures quicker with saturated specimens than when the specimens are dry. The internal pore pressure created as a result of the water present certainly has an influence on the test results. There may be a relationship between the speed of loading and the rate at which the voids are allowed to fill and refill with water. Further research may provide an optimum speed of load creating a failure in minimum time.

The degree of damage caused by early freezing of concrete is a complex relationship dependent upon many factors. The following should be considered: (1) air entrainment will reduce bleeding, hence reduce accumulation of free water;(2) a stiffer concrete mix will have less bleeding;(3) the water-cement ratio and heat of hydration will effect the probable damage;(4) the temperature gradient through the concrete effected by size and location of concrete. These and many more factors can alter the extent of damage caused by early freezing.

Thus, definite conclusions are possible when strict procedures are followed as outlined in the next chapter.

TABLE IV

NUMBER OF CYCLIC LOADS TO FAILURE FOR SAMPLES SUBJECT TO STANDARD CURING CONDITIONS (27)

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate	Rate of Cyclic Load k/min.	ksi/min.	Average Cycles to Failure
D29, D30, D31	66	6.5	6.25	70	300.00	10.60	756
D20, D21, D22	33	5.0	6.16	70	200.00	7.07	559
D32, D33, D34	113	6.5	6.35	70	100.00	3.53	286
D35, D36, D37	90	6.5	6.38	70	50.00	1.77	239

TABLE V

NUMBER OF CYCLIC LOADS TO FAILURE FOR SAMPLES SUBJECT TO EARLY FREEZING CONDITIONS (27)

Test Number	Curing Period Days	Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate	Rate of Cyclic Load k/min.	ksi/min.	Average Cycles to Failure
FD52, 53, 54	72	6.5	6.64	70	300.00	10.60	810
FD43, 44, 45	35	5.0	6.94	70	200.00	7.07	594
FD55, 56, 57	114	6.5	7.34	70	100.00	3.53	466
FD58, 59, 60	98	6.5	7.21	70	50.00	1.77	212

TABLE VI

DURABILITY OF CONCRETE CORE SAMPLES SUBJECT TO CYCLIC LOADING[a] AND FREEZING FIELD CONDITIONS

Test Number	Curing Period Years	Percent Air[c]	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate	Rate of Cyclic Load Kips per Minute	(ksi/min)	Dynamic Modulus $E_D \times 10^3$ ksi	Durability Factor DF	Cycles to Failure
A1	8	1	5.86	70	45.1	(3.58)	4.7	6.7	242
A2	8	1	5.86	70	45.1	(3.58)	5.5	8.9	615
A3	8	1	5.86	70	45.1	(3.58)	4.5	6.8	370
A4	8	1	5.86	70	45.1	(3.58)	5.3	13.3	491
A5	8	1	5.86	70	45.1	(3.58)	5.3	4.4	300
A6	8	1	4.53	70	35.0	(2.78)	4.2[d]	10.0[d]	539
A7	8	1	4.53	70	35.0	(2.78)	4.2	10.0	536
A8[b]	19	5	2.99	70	46.2	(3.67)	4.3	5.3	906

[a]Concrete core samples taken from foundation walls of large reinforced concrete and masonry building. Concrete was cast January 1964 in freezing temperatures, forms were stripped less than 24 hours and air temperature had reached 6°F above zero. No protection was used. Specimen A8 not taken from this structure.

[b]Initial cure conditions unknown.

[c]Air content is estimated for all samples.

[d]A6 was taken at the same time and from the same locality as A7. Cycles to failure were 539 for A6 and 536 for A7. Therefore, the dynamic modulus and durability factors are assumed similar.

TABLE VII

DURABILITY OF CONCRETE SAMPLES SUBJECT TO CYCLIC LOADING AND WINTER CURING CONDITIONS

Test Number	Curing Period Days	Type Cement and Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Durability Factor DF	Remarks
U1, U2	27	I-1	6.10	70	120.75	13.6	Uncovered
U3, U4	27	I-1	6.10	35 + 35	60.38	51.0	Uncovered
U5, U6	26	I-1	6.12	70	120.97	21.0	Covered
U7, U8	26	I-1	6.12	35 + 35	60.48	80.0	Covered
U9, U10	29	I-5	5.23	70	103.51	31.6	Uncovered
U11, U12	29	I-5	5.23	35 + 35	51.75	86.7	Uncovered
U13	29	I-5	5.23	40 + 40	59.15	15.7	Uncovered
U14, U15	33	I-5	5.11	70	101.03	25.6	Covered
U16	33	I-5	5.11	35 + 35	50.52	84.9	Covered
U17, U18	33	I-5	5.11	40 + 40	57.73	35.5	Covered

TABLE VII (Continued)

Test Number	Curing Period Days	Type Cement and Percent Air	Ultimate Static Strength ksi	Cyclic Load Percent of Ultimate[a]	Rate of Cyclic Load k/min.	Durability Factor DF	Remarks
U19, U20	31	III-1	4.85	70	96.13	87.8	Uncovered
U21	31	III-1	4.85	35 + 35	48.07	88.9	Uncovered
U23	31	III-1	4.85	40 + 40	54.93	82.6	Uncovered
U24, U25	44	III-1	4.13	70	81.90	88.0	Covered
U26	44	III-1	4.13	35 + 35	40.95	95.5	Covered
U27, U28	44	III-1	4.13	40 + 40	46.80	95.4	Covered

[a]70% cyclic load means 70% of the ultimate compressive strength was applied as static load. 35 + 35 means 35% of ultimate strength as static load and 35% as cyclic load.

CHAPTER VI

SUMMARY AND CONCLUSIONS

6.1 Summary of Research

Concrete exposed to freezing temperatures while it is still plastic is subject to permanent damage caused by the formation of ice. Even though extended moist curing may restore the compressive strength to levels acceptable by local building codes, the fatigue durability as defined in this research may still be seriously reduced.

A slow cycle fatigue method of test was developed through an extensive laboratory study where concrete damaged by early freezing was compared to similar concrete cured under standard conditions. It was determined that the standard compressive strength of concrete, which is normally used as a means of quality control for concrete in practical applications, could not be used to predict the fatigue durability of concrete.

Air entrainment was found to have a beneficial effect on the fatigue durability of concrete subjected to early freezing and also concrete that is standard cured.

A microscopic evaluation of concrete samples provided a simple means of detecting some of the internal flaws created by freezing of concrete while still plastic.

The number of cyclic loads to cause a complete failure of a concrete specimen was observed. The resonant frequency at frequent intervals during the fatigue test was measured and the dynamic modulus of elasticity determined. A graphical plot of the changing dynamic modulus vs. the number of load cycles indicated a significant relationship between concrete specimens damaged and those not damaged by early freezing. The calculation of a durability factor utilizing the resonant frequency of the specimens provides a means of comparing the effects of early freezing on the fatigue durability of concrete.

Bond cracks around and adjacent to the large aggregate were observed in the microscopic study and were typical of the specimens damaged by early freezing. The slow cycle fatigue test did cause a more rapid deterioration of concrete damaged by early freezing than for concrete which was standard cured. Thus concrete with a compressive strength of 3000 psi not damaged was shown to have a better durability than concrete with a compressive strength of 5900 psi which had been damaged by early freezing.

6.2 Conclusions

The following conclusions can be made from this research:

1. Concrete exposed to freezing temperatures while the concrete is still plastic can be permanently damaged resulting in much lower fatigue durability.

2. A slow cycle fatigue method of test can be used to compare the relative fatigue durability of concrete specimens frozen during the initial curing period to specimens cured under standard conditions. Calculation of a durability factor is possible.

3. The change in the dynamic Young's modulus of elasticity as a result of an increase in the number of cycles of load applied to a concrete specimen is indicative of the concrete fatigue durability. Concrete frozen during the initial curing period produced a larger decrease in dynamic modulus for a constant number of cycles than concrete cured under standard conditions.

4. Concrete frozen during the initial curing period had a lower durability factor, lower compressive strength and failed completely with fewer load cycles than similar concrete cured in a standard manner. Concrete subject to initial cool curing produced an increased compressive strength when compared to the standard cured specimens. No significant change occurred in the durability factor or the number of load cycles to cause complete failure.

5. A microscopic study of concrete samples frozen during the initial curing period showed cracks in the cement matrix adjacent to the coarse aggregate. After eight years the average compressive strength increased from 3000 psi to 5860 psi; however, the bond cracks were still easily identified.

6. There was a significant change in the fatigue life of both standard samples and those subject to early freezing as a result of air entrainment. The number of cycles to failure and the durability factor increased as the air entrainment increased, reaching a maximum near 5 percent.

7. If the concrete was frozen during the initail curing period adequate strength for structural purposes could be obtained with continued moist curing; however, the fatigue durability of the concrete was still seriously decreased.

6.3 Suggestions for Further Work

The effects of reduced bond on aggregates and steel reinforcing needs additional research to determine the nature and extent of damage.

Concrete which may be damaged by freezing temperatures and then cured for only a short period of time should be investigated in detail. This would eliminate the effects of autogeneous healing and may indicate a greater difference in durability as affected by early freezing.

The beneficial effects of cool curing without danger to freezing should be further investigated, especially as related to increase in strength and durability of concrete.

Many concrete structures such as bridges, highway pavements and even buildings are actually subject to slow cycles of load throughout their lives. It seems reasonable to assume that much benefit could be obtained by further studying the effects of slow cycle fatigue as related to concrete in general, and to the effects of rapid drying of fresh concrete, effects of shrinkage cracks, curing conditions and addition of additives. Since the fatigue durability of the concrete structure is of prime importance, the slow cycle fatigue method may prove useful to further the understanding of concrete fatigue durability.

The testing procedure needs to be standardized so that results can be compared more realistically. The following points may be considered:

1. Rate of loading to be constant at 4,000 psi per minute.
2. All specimens must be saturated at a standard temperature of $73^{o}F$ for 48 hours prior to testing.

BIBLIOGRAPHY

(1) McNeese, D. C. "Early Freezing of Non-Air-Entraining Concrete." Jour. of Amer. Conc. Inst., Vol. 49 (December, 1952), pp. 293-300.

(2) Fitch, H. M. "Effect of Low Curing Temperatures on the Strength of Concrete." (Master's Thesis, University of Illinois, 1933.)

(3) Timms, A. G., and N. H. Withey. "Temperature Effects on Compressive Strength of Concrete." Jour. of Amer. Conc. Inst., Vol. 30 (1934), pp. 159-180.

(4) Lord, A. R. "Notes on Walker Drive." Jour. of Amer. Conc. Inst., Vol. 23 (1927), pp. 26-29.

(5) Professor Baus. French paper presented to the meeting of the FIP Commission on Durability held in Moscow, October 14-17, 1967 (Federation Internationale De La Precontrainte, Notes, November, 1969).

(6) Young, R. B. "Job Problems and Practice." Jour. of Amer. Conc. Inst., Vol. 39 (1943), p. 127.

(7) Hagy, E. A. "Job Problems and Practice." Jour. of Amer. Conc. Inst., Vol. 39 (1943), p. 129.

(8) Bauer, Edward E. Plain Concrete, 3rd ed. New York: McGraw Hill, 1949, p. 155.

(9) Abdun-nur, E. A., and R. C. Mielenz. "An Unusual Case of Freezing of Fresh Concrete." Jour. of Amer. Conc. Inst., Vol. 59 (June, 1962), pp. 803-813.

(10) Rollins, Smith and Associates. "Roof Slab Failure." (Unpublished Engineering Report), File 7123B, February, 1972.

(11) Champion, S. Failure and Repair of Concrete Structures. New York: John Wiley & Sons, 1961, pp. 2-9.

(12) Feld, Jacob. Lessons From Failures of Concrete Structures. Amer. Conc. Inst. Monograph No. 1, 1964.

(13) ACI Committee 201. "Durability of Concrete in Service." Jour. of Amer. Conc. Inst., Vol. 59 (December, 1962), pp. 1771-1816.

(14) Whitehurst, E. H. Evaluation of Concrete Properties from Sonic Tests. Amer. Conc. Inst. Monograph No. 2, 1966.

(15). Troxell, George E., E. H. Davis, and W. J. Kelly. Composition and Properties of Concrete, 2nd ed. New York: McGraw Hill Book Company, 1968.

(16) "Standard Method of Test for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens." C215-60, 1968. Book of ASTM Standards, Part 10, p. 155.

(17) ACI Committee 215. "Fatigue of Concrete." Amer. Conc. Inst. Bibliography No. 3, Detroit, Michigan, 1960, 38 pp.

(18) Price, W. H. "Factors Influencing Concrete Strength." Jour. of Amer. Conc. Inst., Vol. 47 (February, 1951), pp. 417-432.

(19) Hou, Kwang-tien. "Effects of Low Temperature During Initial Curing on Concrete Durability." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, 1964.)

(20) Hu, Che-ming. "Effects of Variable Loading and Freezing Temperatures on Concrete Durability." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, 1964.)

(21) Chaurshia, M. S. "Effects of Variable Loading, Low Temperature, and Different Curing Conditions on Concrete Durability (Part I)." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, June, 1969.)

(22) Vohra, M. P. "Effects of Variable Loadings, Low Temperature, and Different Curing Conditions on Concrete Durability (Part II)." (Unpublished Master's Thesis, Brigham Young, Provo, Utah, June, 1969.)

(23) Upadhyaha, H. G. "Investigation of Durability of Concrete." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, 1969.)

(24) Mehta, Purushottam. "An Experimental Investigation of the Physical Change of Normal Concrete Subjected to Dynamic Loading and Freezing Conditions." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, June, 1970.)

(25) Pandit, A. Y. "An Experimental Investigation of the Physical Changes of Air Entrained Concrete Subjected to Dynamic Loading and Freezing Conditions." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, June, 1970.)

(26) Lee, Tang Yang. "Comparison of Durability (of Concrete) of Constant Water to Cement Ratio with different Consistencies Subjected to Dynamic Loading." (Unpublished Master's Thes s, Brigham Young University, Provo, Utah, 1972.)

(27) Doshi, Harishkumar J. "An Experimental Investigation of Air Entrainment Different Curing Conditions, and Rates of Loading on Concrete Durability." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, 1971.)

(28) Doshi, Dinesh J. "An Experimental Investigation of the Durability of Concrete." (Unpublished Master's Thesis, Brigham Young University, Provo, Utah, 1972.)

(29) "Standard Method of Test for Resistance of Concrete Specimens to Rapid Freezing and Thawing." C290-67 & C291-67, 1968. Book of ASTM Standards, Part 10, pp. 213 and 218.

(30) "Standard Method of Making and Curing Concrete Test Specimens in the Laboratory." C192-66, 1967. Book of ASTM Standards, Part 10, p. 148.

(31) "Standard Specifications for Concrete Aggregates." C33-67, 1968. Book of ASTM Standards, Part 10, p. 17.

(32) Pickett, Gerald. "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders." Proceedings, ASTM, Vol. 45 (1945), p. 346.

(33) Obert, L. "Sonic Method of Determining the Modulus of Elasticity of Building Materials Under Pressure." Proceedings, ASTM, Vol. 39 (1939), p. 937.

(34) Hsu, T. T. C., F. O. Slate, G. M. Sturman, and G. Winter. "Microcracking of Plain Concrete and the Shape of the Stress-Strain Curve." Jour. of Amer. Conc. Inst., Vol. 57 (February, 1963), pp. 209-224.

(35) Slate, F. O., and O. Olsefski. "X-Rays for Study of Internal Structure and Microcracking of Concrete." Jour. of Amer. Conc. Inst., Vol. 60 (May, 1963), pp. 575-588.

(36) Meyers, Bernard L., Floyd O. Slate, and George Winter. "Relationship Between Time-Dependent Deformation and Microcracking of Plain Concrete." Jour. of Amer. Conc. Inst., Vol. 66 (January, 1969), pp. 60-68.

(37) Shah, P. Surendra, and Chandra Sushil. "Critical Stress, Volume Change, and Microcracking of Concrete." Jour. of Amer. Conc. Inst., Vol. 65 (September, 1968), pp. 770-781.

(38) Krishaswamy, K. T. "Strength and Microcracking of Plain Concrete Under Triaxial Compression." Jour. of Amer. Conc. Inst., Vol. 55 (October, 1968), pp. 856-862.

Related References

(39) Sexsmith, Robert G. "Reliability Analysis of Concrete Members." Jour. of Amer. Conc. Inst., Vol. 71 (May, 1969), p. 413.

(40) Malhotra, V. M. "Nondestructive Methods for Testing Concrete." Mines Branch Monograph, 875, Department of Energy, Mines and Resources, Ottawa, Ontario, Canada, 1968.

(41) Agrawal, G. L., Leonard G. Tulin, and Kurt H. Gerstle. "Response of Doubly Reinforced Concrete Beams to Cyclic Loading." Jour. of Amer. Conc. Inst., Vol. 43 (July, 1965), pp. 62-71.

(42) Preece, B. W., and J. D. Davies. Models for Structural Concrete. London: CR Books Limited, 1964.

(43) Sinha, B. P., Kurt H. Gerstle, and Leonard G. Tulin. "Response of Singly Reinforced Beams to Cyclic Loading." Jour. of Amer. Conc. Inst., Vol. 39 (August, 1964), pp. 51-56.

(44) Sinha, B. P., Kurt H. Gerstle, and Leonard G. Tulin. "Stress-Strain Relations for Concrete Under Cyclic Loading." Jour. of Amer. Conc. Inst., Vol. 32 (February, 1964), pp. 51-62.

(45) A Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data. (Supplement to Manual on Fatigue Testing No. 91). ASTM No. 91A (1963), p. 12.

(46) Gray, Warren H., John F. McLaughlin, and John D. Antrim. "Fatigue Properties of Lightweight Aggregate Concrete." Jour. of Amer. Conc. Inst., Vol. 41 (August, 1961), p. 149.

(47) McIntosh, J. D. Concrete and Statistics. London: CR Books Limited, 1963.

(48) Verna, John R., and Thomas E. Stelson. "Repeated Loading Effect on Ultimate Static Strength of Concrete Beams." Jour. of Amer. Conc. Inst., Vol. 60 (June, 1963), pp. 422-428.

(49) Verna, John R., and Thomas E. Stelson. "Failure of Small Reinforced Concrete Beams Under Repeated Loads." Jour. of Amer. Conc. Inst., Vol. 59 (October, 1962), pp. 1489-1504.

(50) Hondros, G., J. H. Matthews. "Effects on Physical Properties of Plain Concrete of Repetitive Static Loading." Construction Review, Vol. 34, No. 4 (April, 1962), p. 22-28.

(51) Grover, H. J., S. A. Gordon, and L. R. Jackson. Fatigue of Metals and Structures. Battelle Memorial Institute, Navweps 00-25-534, Revised June 1, 1960.

(52) Hinsley, J. F., and Edwin Gregory. Non-Destrictive Testing. London: MacDonald and Evans LTD, 1959.

(53) Stelson, Th mas E., and John N. Cernica. "Fatigue Behavior of Reinforced Concrete Beams." Proceedings, Amer. Conc. Inst. (August, 1958), No. 55-15.

(54) Chang, Tien S., and Clyde E. Kesler. "Fatigue Behavior of Reinforced Concrete Beams." Proceedings, Amer. Conc. Inst. (August, 1958), No. 55-14.

(55) McCall, John T. "Probability of Fatigue Failure of Plain Concrete Concrete." Proceedings, Amer. Conc. Inst. (August, 1958), No. 55-13.

(56) Nordby, Gene M. "Fatigue of Concrete - A Review of Research." Proceedings, Amer. Conc. Inst. (August, 1958), No. 55-11.

(57) Murdock, John W., and Clyde E. Kesler. "Effect of Range of Stress on Fatigue Strength of Plain Concrete Beams." Proceedings, Amer. Conc. Inst. (August, 1958), No. 55-12.

(58) Bate, S. C. C. "The Strength of Concrete Members Under Dynamic Loading." Proceedings, Symposium on the Strength of Concrete Structures, London, Cement and Concrete Association, 1958, p. 487.

(59) Manual on Fatigue Testing. ASTM Committee E-9 (1949), Special Publication No. 91.

APPENDIX A

THEORETICAL CONSIDERATIONS FOR CALCULATING YOUNG'S MODULUS OF ELASTICITY AND DURABILITY FACTOR

The basic equation governing the frequency of vibration of a bar or rod of elastic material, vibrating transversely without restraint, may be written as (16, 32):

$$n = \frac{k^2 r}{2\pi L^2}\sqrt{\frac{E_D}{d}} \tag{A.1}$$

where

n = dynamic resonant vibrational frequency,

k = a constant depending primarily on the mode of vibration,

L = length of the bar (or rod),

r = radius of gyration,

E_D = dynamic Young's modulus of elasticity,

d = density of the material.

Equation (A.1) is more useful in its rearranged form:

$$E_D = \frac{4\pi^2 d L^4 n^2}{r^2 k^4} \tag{A.2}$$

Substituting for density $d = \frac{\text{Mass } M}{\text{Volume } V}$ in Equation (A.2), it becomes

$$E_D = \frac{4\pi^2 L^4 n^2 M}{r^2 k^4 V} \tag{A.3}$$

putting Mass $M = \frac{\text{Weight } W}{\text{Gravitational Constant } g}$, Equation (A.3) is written as

$$E_D = \frac{4\pi^2 L^4 n^2 W}{r^2 k^4 Vg} \qquad \text{(A.4)}$$

Substituting $k^2 = \frac{\text{Moment of Inertia } I}{\text{Cross-sectional area } A}$ and Volume V = Length L x Area, Equation (4) reduces to:

$$E_D = \frac{4\pi^2 L^3 n^2 W}{Ik^4 g} \qquad \text{(A.5)}$$

Equation (A.5) can be written in more convenient form as:

$$E_D = CWn^2 \qquad \text{(A.6)}$$

where

$$C = \frac{4\pi^2 L^3}{Ik^4 g} \qquad \text{(A.7)}$$

In relation to Equation (A.7) the more practical expressions which are usable in sonometer work are discussed below.

Consider just a bar which vibrates flexurally, a cross-sectional element may be thought of as actually executing two movements: a motion of translation laterally which is in the direction of vibration, and one of rotation relative to the position of the unbent neutral axis. In both of these cases, the effects of inertia must be considered. Depending both on the dimensions of the sample and on the material, the error introduced by neglecting the effects of rotary inertia is not very large. If the thickness of the bar is a relatively large fraction of the length, then the rotary inertia must be taken into account. In this case, especially for rectangular bars or irregular corss-section bars, the driving force axis does not intersect the unbent neutral axis, although it is perpendicular to the surface specimen. There is a distance between the driving force axis and the unbent neutral axis. In the case, we should consider the rotary inertia of the cross section. But in this investigation the specimens all are circular cross-section cylinders. The driving force is perpendicular to the surface and also intersects the unbent neutral axis. There is no distance between driving force axis and unbent neutral axis (or if there is any, it is very small). Therefore, rotary inertia in this experimental work can be neglected.

On the other hand, one should consider the cross-section under the driving force. The cross-section is being subjected to alternate lateral contractions and expansions which may be taken into account by the introduction of Poisson's ratio. In Equations (A.6) and (A.7) the C becomes C = C'T in which

$$C' = \frac{4\pi^2 L^3}{I m^4 g}$$

and $T = \frac{m^4}{k^4}$ is Goens' correction factor, where m represents the limiting value of k.

A.1 Discussion of the Formula $E_D = CWn^2$

The computation of the dynamic Young's modulus of elasticity was based on resonant frequency tests. The general testing method provides for the determination of dynamic modulus on the basis of either transverse resonant frequency or longitudinal resonant frequency. For this thesis, the dynamic Young's modulus of elasticity was calculated from fundamental transverse frequency, weight and the dimensions of the test specimen as follows:

Dynamic E_D = Dynamic Young's modulus of elasticity, psi;

W = weight of the specimen, pounds;

n = fundamental transverse frequency, in cycles per second;

C = 0.00416 $(L^3T)/(d^4)$ sec^2 per square inch for a cylinder;

L = length of the specimen, inches;

d = diameter of the cylinder, inches;

T = a correction factor which depends on the relation of the radius of gyration to the length of the specimen, and on Poisson's ratio.

A.2 Determination of Correction Factor

The values of T for Poisson's ratio of 1/6 are derived from Figure 1 of the paper by Gerald Pickett, "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders," A.S.T.M. Proceedings, Vol. 45, p. 346 (1945).

For a different value of Poisson's ratio, and given r/L, T may be calculated from the following relationship:

$$T' = T \frac{1 + (0.26\mu + 3.22\mu^2)\ r/L}{1 + 0.1328\ r/L}$$

where T is taken from Table VIII for the given r/L. For example:

Given:

6 in. by 12 in. concrete cylinder

μ = assume 1/6

W = 30.0 lbs.

n = 4,000 CPS

Find E_D

Solution:

From Equation (6)

$$E_D = (0.00416L^3T/d^4)Wn^2$$

To find T

$$r = d/4 = 6/4 = 1.50$$

$$r/L = 1.50/12 = 0.125$$

From Table VIII, T = 2.11.

Therefore:

$$E_D = 0.00416 \frac{(12)^3 \times 2.11}{(6)^4} \times 30.0 \times (4{,}000)^2$$

$$E_D = 5.6 \times 10^6 \text{ lbs/in.}^2.$$

A.3 Sonic Modulus Equipment for Determining Young's Dynamic Modulus

Sonic modulus equipment consists of the following:

a. Oscillator and power amplifier. The heart of the electro sonometer is an electronic audio frequency oscillator, the function of which is to generate electrical audio frequency voltages. In Figure 19 the sonometer block diagram shows the electrical output of the oscillator is ultimately converted to mechanical vibrations. The electrosonometer's oscillator is a Hewlett-Packard type 200BR. The frequency of the oscillator has a guaranteed accuracy of less than 2 percent variation over the entire frequency output range of 20 cycles per second to 20,000 cycles per second. The oscillator output is introduced into an amplifier for amplification to a level suitable for producing mechanical vibrations.

TABLE VIII

VALUES OF CORRECTION FACTOR T

r/L	T	r/L	T
0.00	1.00	0.09	1.60
0.01	1.01	0.10	1.73
0.02	1.03	0.12	2.03
0.03	1.07	0.14	2.36
0.04	1.13	0.16	2.73
0.05	1.20	0.18	3.14
0.06	1.28	0.20	3.58
0.07	1.38	0.25	4.78
0.08	1.48	0.30	6.07

b. Driver, pick-up, and pick-up amplifier (see Figure 19). The power output of the amplifier is fed into a magnetic driver to produce mechanical vibrations. Mechanical vibrations are sensed by a piezo-electric crystal pick-up utilizing a steel needle in a manner similar to a phonograph. The pick-up is mounted on a specially designed heavy-base stand, and converts the mechanical vibrations to electrical vibrations. Shielded cable carries the low level electrical output to an amplifier that, in turn, raises the level of the pickup signal to a value where, after electron tube rectification, it may be indicated on a meter.

c. Oscilloscope. Vibration resonance is clearly indicated both by a meter and by a Lissajous figure on a cathode oscilloscope.

A.3.1 Sonic Test

After a limited number of cycles on concrete specimen, the sonic or dynamic elasticity was determined by determining the resonant transverse flexural frequency of the cylinder as follows:

a. The oscilloscope and oscillator were turned on. The cylinder was placed on two knife edge supports, each positioned at a distance of 0.224L from the end (see Figure 21).

b. The end of the driver hammer was placed against the side of the sample, as close as possible to the end of the side face and parallel to the end surface of the cylinder.

c. The pick-up was placed on the top of the specimen as close to th the end as possible. The pick-up cartridge assembly was vertically positioned on the stand so that the needle was resting on the sample with a

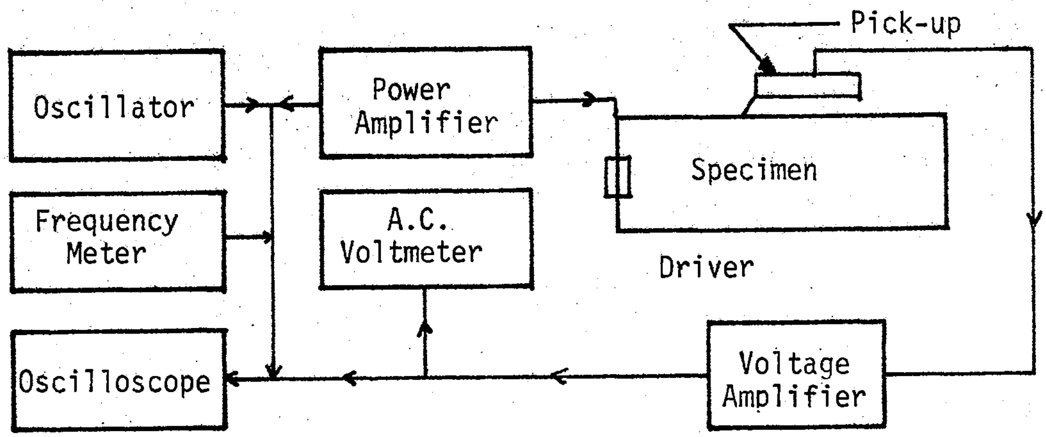

Figure 19. Sonometer Block Diagram

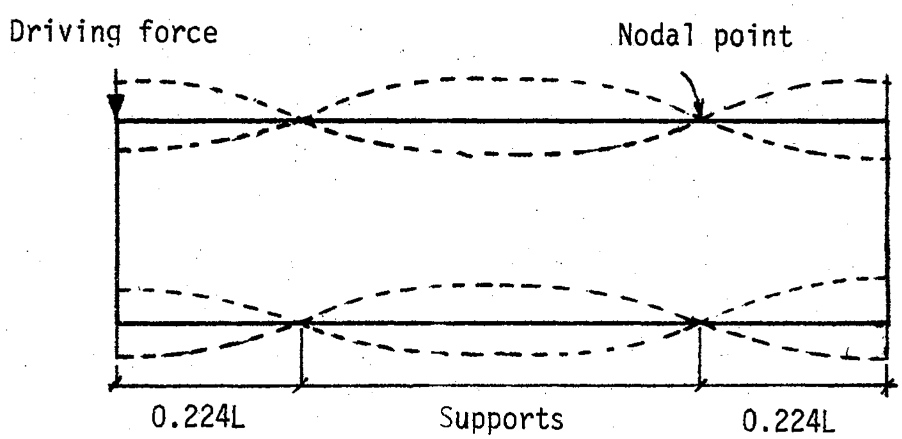

Figure 20. Specimen Placed on Two Rubber Supports

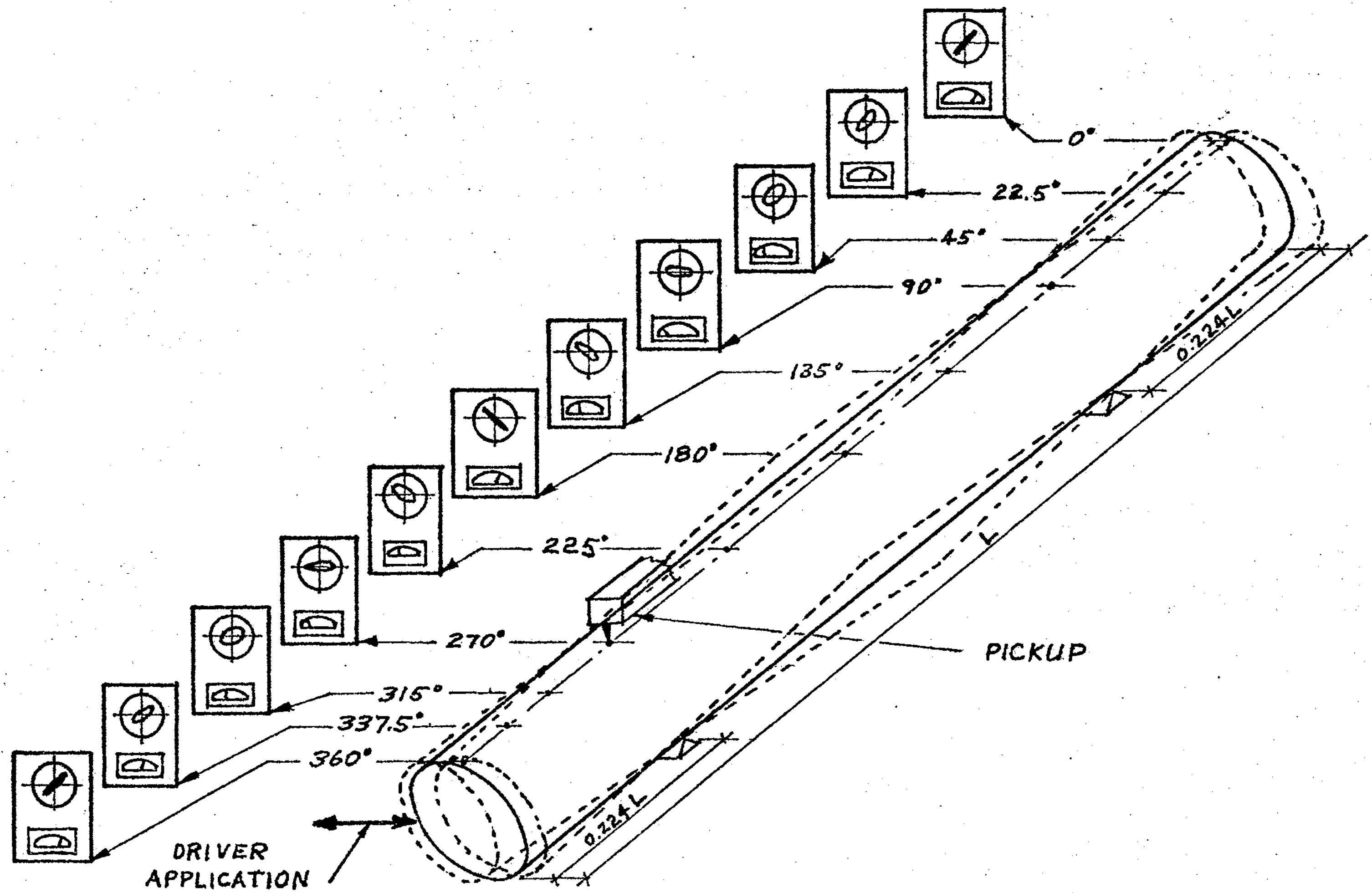

Figure 21. Cylinder Vibrating at Fundamental Transverse Resonant Frequency

slight pressure. The long dimension of the pick-up cartridge was parallel to the specimen dimension L.

d. The output range selector was set at the "100" position, using fine frequency control to get the frequency. It was started at a lower frequency and increased gradually until a reasonable flat or slightly elliptical straight line could be observed at an angle of approximately 45° on the oscilloscope. This condition is described in Figure 21. The pick-up was moved along the top face of the specimen and the resonant vibration of the specimen in the fundamental transverse mode caused the pick-up to encounter a total of two vibrational nodes and three vibrational antinodes. The axis of the Lissajous pattern made one complete 360° revolution in one complete excursion down the entire top length of the specimen (see Figure 21). At a certain frequency, the Lissajous figure meets the requirement as shown in Figure 21. This frequency is the one to be used in the equation

$$E_D = CWn^2$$

to calculate the dynamic modulus of elasticity.

A.3.2 Dynamic Young's Modulus of Elasticity

Modulus of Elasticity. It is the ratio of unit stress to unit deformation, within the proportional limit. This definition implies that materials used should be elastic. To make it more general, it is defined as the ratio of an increment of stress to a corresponding increment of deformation.

$$\text{Modulus of Elasticity} = \frac{\text{Unit Stress}}{\text{Unit Strain}} .$$

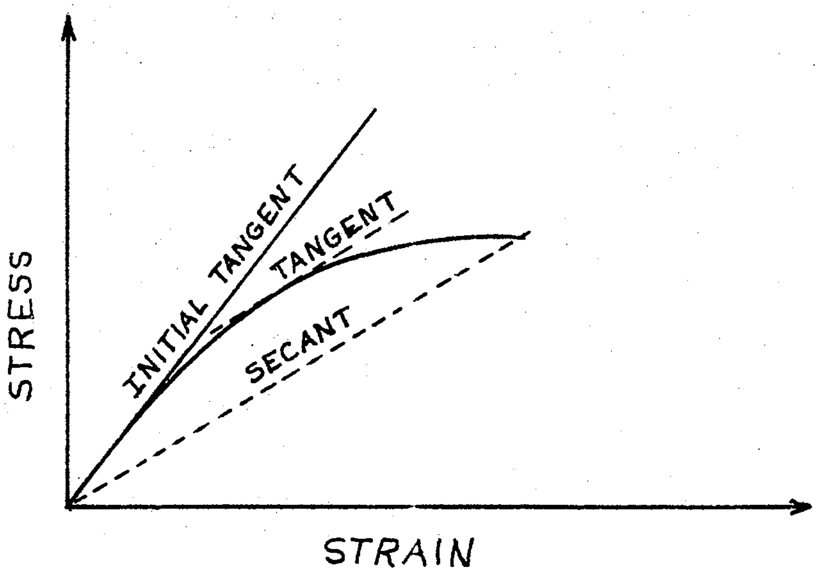

Figure 22. Three Methods of Determining Modulus of Elasticity From a Stress-Strain Curve

Perfectly elastic material has a constant modulus of elasticity. The modulus of elasticity is a measure of the stiffness of the material, or of the resistance of the material to deformation. Since concrete, like most other structural materials, is imperfectly elastic, the stress-strain diagram is a curved line. Hence, three methods have been used for computing moduli of elasticity from a stress-strain diagram as shown in Figure 22. They are as follows:

1. The "initial tangent modulus" (E_i) is represented by the slope of a tangent to the stress-strain curve, drawn through the origin.

2. The "tangent modulus of elasticity" (E_t) is represented by the slope of a line drawn tangent to the stress-strain curve at any point A on the curve.

3. The "secant modulus of elasticity" (E_s) is represented by the slope of a line drawn from the origin to any point B on the curve.

Dynamic Modulus of Elasticity. The dynamic modulus of elasticity obtained by a dynamic resonance method on a prism or cylinder of concrete is always higher than that obtained from a conventional stress-strain method. Therefore, the modulus of elasticity is called the dynamic modulus of elasticity to distinguish it from the other, which is called the static modulus of elasticity. This difference is due to the fact that the results of the dynamic method are not affected by creep of concrete. In a sonic test, since the deformations are considered to be very small, the modulus of elasticity so determined may be considered as the initial tangent modulus.

A.3.3 Durability Factor

Repeated loading will contribute to a more rapid deterioration of damaged concrete, and the change in value of the dynamic modulus will be a measure of the durability factor of the concrete. Both of the standard freezing and thawing tests, A.S.T.M. C290-67 and C291-67, provide for computation of durability factor based on resonant frequency tests. In this same way, we can calculate durability factor of concrete for cyclic load tests as follows:

a. Relative dynamic modulus of elasticity, percentage, can be shown in the formula

$$P_c = \frac{n_i^2}{n_o^2} \times 100 \qquad \text{(A.8)}$$

where

P_c = relative dynamic Young's modulus of elasticity, percentage, after N cycles of cyclic load,

n_o = fundamental transverse frequency at 0 cycles of cyclic load,

n_i = fundamental transverse frequency after N_i cycles of cyclic load.

The above calculation of relative dynamic Young's modulus of elasticity is based on the assumption that the dimensions and weight are not changed during the test. If the specimen is disintegrated, the assumption is not true; however, if the test is just to be used to make comparisons between the relative dynamic Young's moduli of different specimens or of different concrete formulations, then the P_c is adequate for the purpose.

b. The durability factor of the test specimens can be obtained from the following formula:

$$DF = \frac{P_c N_i}{M} \tag{A.9}$$

where

DF = durability factor of the test specimen,

P_c = relative dynamic Young's modulus of elasticity at N cycles of dynamic load, percentage,

N_i = number of cycles at which P_c reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the cycle load is to be terminated,

M = specified number of cycles at which the dynamic load is to be terminated.

Substituting Equation (A.8) into (A.9)

$$DF = \frac{n_i^2 N_i}{n_o^2 M} \times 100. \tag{A.10}$$

In this investigation, the value of M = 1800 cycles was taken to reduce the time of testing and to compare the testing results with that of the previous investigations.

Consider three possibilities for determining the durability factor of concrete specimens:

(I) $N < 1800$

(II) $N = 1800$

(III) $N > 1800$.

Case I. If the cylinder breaks at $N < 1800$, then it is necessary to know the value of n_i and N_i in Equation (A.10). The following steps can be followed to find the value of n_i and N_i:

1. Assume $P_c = 80\%$;
2. Find n_i from Equation (A.8);
3. Interpolate the value of N_i for n_i from the testing results as shown in Figure 23;

   $N_i = N_{i-1} + X$;

but from similar triangles

$$X = (N_{1+i} - N_{i-1} - n_{i-1}) \frac{n_{i-1} - n_i}{n_{i-1} - n_{i+1}}$$

substituting

$$N_i = N_{i-1} + (N_{i+1}) \frac{n_{i-1} - n_i}{n_{i-1} - n_{i+1}} ; \qquad \text{(A.11)}$$

similarly,

$$n_i = n_{i-1} - (N_i - N_{i-1}) \frac{n_{i-1} - n_{i+1}}{N_{i+1} - N_{i-1}} \qquad \text{(A.12)}$$

where

N_i = number of cycles of n_i;

N_{i-1} = number of cycles at which n is the next higher frequency;

N_{i+1} = number of cycles at which n is the next lower frequency;

n_{i-1} = n corresponding to N_{i-1};

n_{i+1} = n corresponding to N_{i+1}.

Case II. If the concrete cylinder is checked at N = 1800, then n_i corresponding to $N_i = 1800$ is known. The durability factor can be determined from Equation (A.9).

Case III. If the concrete cylinder breaks at N > 1800, then determine the value of n_i corresponding to $N_i = 1800$ by interpolation. The value of n_i can be found by substituting $N_i = 1800$ into Equation (A.12),

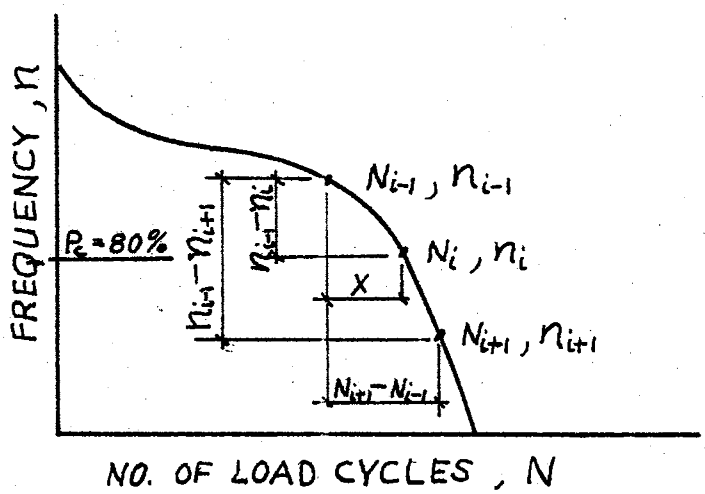

Figure 23. Proportional Relationship Between Frequency and Load Cycles

then:

$$n_i = n_{i-1} - \frac{n_{i-1} - n_{i+1}}{N_{i+1} - N_{i-1}} (1800 - N_{i-1}) \tag{A.13}$$

where

n_i = frequency at N_i = 1800 cycles;

n_{i-1} = frequency at the next lower number of cycles;

n_{i+1} = frequency at the next higher number of cycles;

N_{i-1} = cycles corresponding to n_{i-1};

N_{i+1} = cycles corresponding to N_{i+1}.

Out of the three cases listed above, the smallest value was taken as representative of the durability factor for the specimen.

APPENDIX B

SAMPLE CALCULATIONS

Sample calculations of the durability of concrete are shown for cases I, II, and III listed in Appendix A. The data for the calculations are taken from the test results of the specimens.

Test Number	Weight in lbs.	Number Cycles N	Frequency cps n	$E_D \times 10^3$ ksi	Durability Factor DF
HB-5	28.8	0	4000	5.40	
		100	3910	5.16	
		250	3880	5.06	
		460	3780	4.82	22.95
		900	2810	2.66	
		989	0	0	
HB-6	28.70	0	4010	5.41	
		50	3970	5.30	
		100	3900	5.12	
		300	3950	4.98	
		860	3850	4.98	
		1250	3800	4.86	
		1480	3750	4.73	
		1800	3700	4.60	
					84.70
HB-7	29.10	0	4000	5.46	
		175	3920	5.24	
		650	3890	5.16	
		875	3830	5.00	
		1250	3780	4.91	
		1500	3780	4.91	88.60
		2110	3750	4.80	

Case I. Find the dynamic modulus of elasticity and durability factor from the data above for specimen HB-5.

Solution:

a. Dynamic modulus of elasticity, from Equation (6) of Appendix A:

$$E_D = CWn^2$$

for a 6" x 12" cylinder size;

$C = 0.00416\ L^3T/d^4\ sec^2$ per sq. in.

$L = 12$ inches

$d = 6$ inches

$\mu = 1/6$

$I = AK^2 = \frac{\pi d^2}{4} \times \frac{d^2}{4}$

where:

$K = d/4 = 1.5$

therefore

$K/L = \frac{1.5}{12} = 0.125$

By interpolating the value of T from the correction table in Appendix A;

$$T = 2.1125 \text{ for } \frac{K}{L} = 0.125$$

Then substituting and solving, E_D becomes

$$E_D = 11.717 \times 10^{-3} Wn^2$$

$$E_D = 11.717 \times 10^{-3} \times 28.8 \times 4000^2$$

$$E_D = 5.4 \times 10^6 \text{ psi}$$

b. Durability factor

Given:

$n_o = 4000$

$n_i = ?$

$M = 1800$

$N_i = ?$

Now to find the durability factor (DF) first consider Equation (8), Appendix A:

$$P_c = \frac{n_i^2}{n_o^2} \times 100$$

Assume $P_c = 80\%$ and solve for n_i

$$80 = \frac{n_i^2 \times 100}{(4000)^2}$$

$$n_i = 3578$$

Next, determine N_i from Equation (11), Appendix A:

$$N_i = N_{i-1} + (N_{i+1} - N_{i-1}) \frac{n_{i-1} - n_i}{n_{i-1} - n_{i+1}}$$

where:

$N_{i-1} = 460$

$N_{i+1} = 650$

$n_{i-1} = 3780$

$n_{i+1} = 3090$

then:

$$N_i = 460 + (650 - 460) \frac{3780 - 3578}{3780 - 3090}$$

$$= 515.6$$

use:

$$N_i = 516$$

Now substituting into Equation (10), Appendix A:

$$DF = \frac{n_i^2}{n_o^2} \frac{N_i}{M} \times 100$$

Assume M = 1800 cycles:

$$DF = \frac{3578^2}{4000^2} \times \frac{516}{1800} \times 100$$

$$= 22.95$$

Case II. Find the durability factor for specimen HB-6.

Given:

$n_o = 4010$

$n_i = 3700$

$N_i = 1800$

$M = 1800$

From Equation (10), Appendix A:

$$DF = \frac{n_i^2}{n_o^2} \times \frac{N_i}{M} \times 100$$

$$= \frac{(3700)^2}{(4010)^2} \times \frac{1800}{1800} \times 100$$

$$= 84.7$$

Case III. Find the durability factor for specimen HB-7.

Given:

$n_{i-1} = 3780$

$N_{i-1} = 1500$

$n_{i+1} = 3750$

$N_{i+1} = 2110$

$n_o = 4000$

$N_i = 1800$

From Equation (13), Appendix A:

$$n_i = n_{i-1} - \frac{n_{i-1} - n_{i+1}}{N_{i+1} - N_{i-1}} (1800 - N_{i-1})$$

$$= 3780 - \frac{3780 - 3750}{2110 - 1500} (1800 - 1500)$$

$$= 3765$$

Then from Equation (10), Appendix A:

$$DF = \frac{n_i^2}{n_o^2} \times \frac{N}{M} \times 100$$

$$DF = \frac{3765^2}{4000^2} \times \frac{(1800)}{1800} \times 100$$

$$DF = 88.6$$

APPENDIX C

TEST DATA

Curing Conditions

After casting, the specimens were cured in two different conditions: (a) standard curing condition, and (b) early freezing condition. Usually for each group a total of ten specimens were cast. Five specimens from the batch were removed from the mold after twenty-four hours of air curing at 72°F and then transferred to the fog room under standard conditions at 73°F and 90 to 100 percent humidity.

The remaining five specimens from the same batch were stripped after six hours of air curing, allowing sufficient time for safe handling. These specimens were carefully placed in the freezer maintained at -10°F or as noted in data to attain the early freezing condition. The specimens were frozen for twenty-four hours and then transferred to the fog room. Specimens were placed in a tank containing lime water a minimum of twenty-four hours prior to testing to insure 100 percent saturation. Specimens also remained saturated during testing in the special apparatus provided.

Unless otherwise noted 70 percent of the average compressive strength was used as the cyclic load. All specimens were moist cured until tested unless otherwise noted.

Test Number 1S

Specimens: Sand and gravel concrete, 4 in. x 8 in. cylinders, 2 in. slump.

Type of Cement: I, 1 percent air content.

Rate of Loading: One cycle per minute or as shown in table below.

Testing Condition: Tested immediately after removal from fog room.

28 day Compression Strength		% of the 28 day Compression Strength Used as the Cyclic Load		Rate of Cyclic Load K/min
1S-2	5900 psi	1S-1	56% or 3300 psi	41.6
1S-3	4280 psi	1S-4	56% or 2400 psi	30.2
1S-5	4420 psi	1S-6	54% or 2390 psi	30.1
1S-7	4540 psi	1S-8	53% or 2400 psi	30.2
1S-9	4780 psi	1S-10	54% or 2580 psi	32.5

Curing Method

(4 in. x 8 in. cylinders)

Control: 1S-1, 1S-2 — Cured in air (70°F) for 17 hrs , then cured in a fog mist 73° ± 2°F and 90% humidity for the rest of the 28 day cure period or longer.

Test specimens: 1S-3 through 1S-10 — Cured in air for 17 hrs , then frozen at -10°F for a period of 24 hrs , then placed in a fog mist for the rest of the 28 day cure period or longer.

Test Number 2S

Specimens: Sand and gravel concrete, 4 in. x 8 in. cylinders, 2 in. slump.

Type of Cement: I, 1 percent air content.

Rate of Loading: One cycle per minute or as shown in table below.

Testing Condition: Tested immediately upon removal from fog room.

28 day Compression Strength		% of the 28 day Compression Strength Used as the Cyclic Load		Rate of Cyclic Load K/min
2S-2	6220 psi	2S-1	57% or 3540 psi	44.6
2S-4	4560 psi	2S-3	57% or 2600 psi	32.8
2S-6	4180 psi	2S-5	57% or 2380 psi	30.0
2S-8	4200 psi	2S-7	57% or 2390 psi	30.1

Cylinder 2S-5 after being loaded 805 times with the cyclic load, the Dynamic Modulus of Elasticity of this cylinder was 2,200,000 psi. The age of the cylinder at this time was 28 days. Seven months later after the cylinder had been cured in standard air the Dynamic Modulus of Elasticity of this cylinder was 3,880,000 psi , a gain of 1,680,000 psi in 7 months' time; the cylinder broke at 5950 psi , a gain of 1,770 psi in strength from its companion cylinder 2S-6 which was used for a control for 2S-5.

Curing Method

(4 in. x 8 in. cylinders)

Control: 2S-1, 2S-2 — Cured in air (70°F) for 24 hrs , then cured in a fog mist 73° ± 2°F and 90% humidity for the rest of the 28 day cure period, or longer.

Test specimens: 2S-3 through 2S-9 — Cured in air for 24 hrs , then frozen at a -10°F for 48 hrs , then cured in a fog mist for the rest of the 28 day cure period or longer.

Test Number 1LA

Specimens: Lightweight, expanded shale, concrete, 4 in. x 8 in. cylinders.

Type of Cement: I, 9 percent air content.

Rate of Loading: One cycle per minute or as shown in table below.

Testing Condition: Tested immediately upon removal from fog room.

28 day Compression Strength		% of the 28 day Compression Strength Used as the Cyclic Load		Rate of Cyclic Load K/min
1LA-1	2790 psi	1LA-2	40% or 1115 psi	14.0
		1LA-3	70% or 1950 psi	24.5
1LA-8	2320 psi	1LA-7	40% or 926 psi	11.3
1LA-5	1640 psi	1LA-6	40% or 656 psi	8.3
1LA-10	1200 psi	1LA-11	40% or 480 psi	6.0

Curing Method

(4 in. x 8 in. cylinders)

Control: 1LA-1, 1LA-2, 1LA-3 — Cured in air (70°F) for 24 hrs , then cured in a fog mist (73° ± 2°F and 90% humidity) for the rest of the 28 day cure period.

Test specimens: 1LA-4, 1LA-5, 1LA-6 — Cured in air for 24 hrs , then frozen at a -10°F for a period of 24 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test specimens: 1LA-7, 1LA-8, 1LA-9 — Cured in air for 48 hrs , then frozen at -10°F for a period of 24 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test specimens: 1LA-10, 1LA-11, 1LA-12 — Cured in air for 6 hrs , then frozen at -10°F for a period of 24 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test Number 1SA

Specimens: Sand and gravel concrete, 4 in. x 8 in. cylinders, 4 in. slump.

Type of Cement: I, 5 percent air content.

Rate of Loading: One cycle per minute or as shown in table below.

Testing Condition: Tested immediately upon removal from fog room.

28 day Compression Strength		% of the 28 day Compression Strength Used as the Cyclic Load		Rate of Cyclic Load K/min
1SA-1	6740 psi	1SA-2	35% or 2360 psi	29.7
		1SA-3	50% or 3370 psi	42.5
		1SA-4	60% or 5050 psi	63.6
1SA-5	6740 psi	1SA-6	35% or 2360 psi	29.7
1SA-8	6740 psi	1SA-7	35% or 2360 psi	29.7
1SA-9	2070 psi	1SA-10	35% or 725 psi	9.1
1SA-11	5250 psi	1SA-12	35% or 1840 psi	23.2

Curing Method

(4 in. x 8 in. cylinders)

Control: 1SA-1, 1SA-2, 1SA-3, 1SA-4 — Cured in air (70°F) for 20 hrs , then cured in a fog mist 73° ± 2°F and 90% humidity for the rest of the 28 day cure period.

Test specimens: 1SA-5, 1SA-6 — Cured in air for 20 hrs , then cured in fog mist for 4 hrs , then frozen at -10°F for 24 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test specimens: 1SA-7, 1SA-8 — Cured in air for 20 hrs , then cured in fog mist for 4 hrs , then frozen for 48 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test specimens: 1SA-11, 1SA-12 — Cured in air for 20 hrs , then cured in fog mist for 4 hrs , then frozen for 24 hrs , then cured in a fog mist for 24 hrs , then frozen for 24 more hrs , then cured in a fog mist for the rest of the 28 day cure period.

Test specimens: 1SA-9, 1SA-10 — Cured for 20 hrs in air, then cured in fog mist for 4 hrs , then frozen for 24 hrs , then cured in a temp. of 192°F for 24 hrs , then cured in a fog mist for the rest of the 28 day cure period.

Specimens: Concrete core samples taken from large reinforced concrete and masonry building. Specimens were sand and gravel and were 3.75 in.x 8 in.cylinders.

Type of Cement: I, 1 percent air content (estimated).

Rate of Loading: One cycle per minute.

Curing Method: Concrete was cast in January 1963 in freezing temperatures. Forms were stripped less than 24 hours and temperatures had reached 6°F above zero. No protection or additives was used. Frost on exterior of concrete was heavy. Age at test time was 8 years.

Testing Condition: Saturated

Results of Compression Test

Test Number	Failure Load lbs	Average Failure Load, lbs	Average Failure Stress, psi
1	64,500		
2	58,750	63,750	5790
3	68,000		

Results of Cycle Load Test

Test Number	Weight lbs	Number Cycles N	Frequency CPS n	$E_D \times 10^6$ psi	DF	Remarks
A1	7.7	0	5300	4.7		
		103	5000	4.2	6.7	
		206	4600	3.6		
		242	0	0		Failure
A2	7.7	0	5700	5.5		
		200	5100	4.4		
		300	4800	3.9	8.9	
		400	4600	3.6		
		608	3700	2.3		
		615	0	0		Failure
A3	7.5	0	5500	4.5		
		112	5090	4.2	6.8	
		344	4700	3.6		Cracks
		370	0	0		Failure

Specimens:	Concrete core samples taken from large reinforced concrete and masonry building. Specimens were of sand and gravel and were 3.75 in. x 8 in. cylinders.
Type of Cement:	I, 1 percent air content (estimated).
Rate of Loading:	One cycle per minute.
Curing Method:	Concrete was cast in January 1963 in freezing temperatures. Forms were stripped less than 24 hours and temperature had reached 6°F above zero. No protection or additives was used. Frost on exterior of concrete was heavy. Age at time of test was 8 years.
Testing Condition:	Saturated

Results of Compression Test

Test Number	Failure Load lbs	Average Failure Load, lbs	Average Failure Stress, psi
1	61,000	66,125	5984
2	71,250		

Results of Cycle Load Test

Test Number	Weight lbs	Number Cycles N	Frequency CPS n	$E_D \times 10^6$ psi	DF	Remarks
A4	7.5	0	5700	5.3		
		200	5300	4.6	13.3	New Caps
		300	5100	4.3		
		400	4800	3.8		
		491	0	0		Failure
A5	7.5	0	5700	5.3		
		100	5100	4.3	4.4	
		200	4400	3.2		
		300	Saved from failure			Cracks

Specimens: Concrete core samples taken from large reinforced concrete and masonry building. Specimens were sand and gravel and were 3.75 in. x 8 in. cylinders.

Type of Cement: I, 1 percent air content (estimated).

Rate of Loading: One cycle per minute.

Curing Method: Concrete was cast in January 1963 in freezing temperatures. Forms were stripped less than 24 hours and temperatures reached 6°F above zero. No protection was used. Age of specimens was 8 years.

Testing Condition: Saturated

Results of Compression Test

Test Number	Failure Load lbs	Average Failure Load, lbs	Average Failure Stress, psi
1	47,500	50,000	4525
2	52,500		

Results of Cycle Load Test

Test Number	Weight lbs	Number Cycles N	Frequency CPS n	$E_D \times 10^6$ psi	DF	Remarks
A6	7.4	0	2050			Error in frequency from loose wire
		300				
		539	Failure			
A7	7.6	0	5000	4.2		
		210	4500	3.4	10.0	
		425	4100	2.8		
		536	0	0		Failure

Specimens: Concrete core samples taken from private residence foundation. Specimens were sand and gravel and were 3.75 in. x 8 in. cylinders.

Type of Cement: I, 5 percent air content (estimated).

Rate of Loading: Two cycles per minute.

Curing Method: Initial curing conditions were unknown. Age at time of test was approximately 19 years.

Testing Condition: Saturated

Results of Compression Test

Test Number	Failure Load lbs	Average Failure Load, lbs	Average Failure Stress, psi
1	33,000	33,000	2990

Results of Cycle Load Test

Test Number	Weight lbs	Number Cycles N	Frequency CPS n	$E_D \times 10^6$ psi	DF	Remarks
A8	7.2	0	5100	4.3		
		126	4500	3.4	5.3	
		315	4300	3.1		
		432	4200	3.0		
		571	4000	2.6		
		733	3800	2.4		
		889				
		906				Failure

VITA

Arnold Wilson

Candidate for the Degree of

Doctor of Philosophy

Thesis: DURABILITY OF CONCRETE AND CONCRETE STRUCTURES BY SLOW CYCLE FATIGUE

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Payson, Utah, February 1, 1933, the son of Mr. and Mrs. Robert L. Wilson.

Education: Graduated from Springville High School, Springville, Utah, in May 1951. Graduated with a 5-year Bachelor of Engineering Science degree in 1957, from Brigham Young University, with a major in Civil Engineering. Graduated with a Master of Science degree in 1962, from Brigham Young University with a structure major in Civil Engineering. Attended Oklahoma State University in Summer of 1964, with a National Science Foundation Fellowship and also during the academic year 1964-65 with a Continental Oil Company Fellowship. Requirements were completed for the Doctor of Philosophy degree from Oklahoma State University in December, 1973.

Professional Experience: Associate Professor of Civil Engineering at Brigham Young University with 16 years of teaching experience. Registered Professional Engineer in Utah with considerable structural design experience in steel and reinforced concrete multistory buildings as well as industrial buildings. Design engineer for large steel space frame roof of the New Activities Center at Brigham Young University 340 ft. by 380 ft. clear span. Design and construction of concrete thin shell structures including hypar shapes, domes, elliptical shells. Consulting work includes, concrete, lightweight concrete, experimental stress analysis as well as structures in steel and concrete. Author of a number of publications in structures and concrete materials areas.

Professional Organization: American Concrete Institute, Prestressed Concrete Institute, International Association for Shell Structures, and Sigma Xi.