A STUDY OF THE MECHANISM OF FATIGUE IN CEMENT PASTE AND PLAIN CONCRETE

MAY 1965

NO. 6

by

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Final Report

A STUDY OF THE MECHANISM OF FATIGUE IN CEMENT PASTE AND PLAIN CONCRETE

May 18, 1965

File: 5-5-4
Project: C-36-19-4D

To: K. B. Woods, Director
Joint Highway Research Project

From: H. L. Michael, Associate Director
Joint Highway Research Project

Attached is a report entitled "A Study of the Mechanism of Fatigue in Cement Paste and Plain Concrete." The report was prepared by Professor J. D. Antrim under the direction of Professor J. F. McLaughlin. Professor Antrim also used this report as his thesis for the Ph. D. degree.

Professor Antrim is now an Assistant Professor on the staff of the Department of Civil Engineering, Clemson University, Clemson, South Carolina.

Respectfully submitted,

Harold L. Michael

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Purdue University
Lafayette, Indiana
May 18, 1965

ACKNOWLEDGMENTS

This investigation was sponsored by the Joint Highway Research Project of Purdue University, Professor K. B. Woods, Director. The writer is very grateful to this organization for providing the necessary financial support.

Deep appreciation is expressed to Professor J. F. McLaughlin, Research Engineer, Joint Highway Research Project, for his assistance during the course of the research and in the preparation and review of this thesis.

The writer also wishes to thank Professor A. D. M. Lewis for his invaluable assistance in matters pertaining to the Krouse-Purdue Fatigue Testing Machine.

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ABSTRACT

This investigation was concerned with the determination of the mechanism of fatigue in cement paste and plain concrete. The cement pastes used were made with water-cement ratios of 0.70 and 0.45 by weight and these same water-cement ratios were used in concretes containing natural aggregates and concrete containing synthetic aggregates. Cylindrical specimens, 2 inches in diameter by 4 inches in height, were used for testing the cement paste and cylindrical specimens, 3 inches in diameter by 6 inches in height, were used for testing the concretes. Specimens were tested in a saturated condition and at moisture contents less than that at saturation. The unconfined static compressive strength of each series was determined by testing numerous cylinders in static compression. Other cylinders were tested in compression at specific stress levels at a speed of 1000 cycles per minute in the Krouse-Purdue Axial-load Fatigue Testing Machine. Over 150 specimens were tested in fatigue and over 500 specimens were tested statically.

It was found that the fatigue behavior of cement paste is sensitive to changes in the water-cement ratio of the paste and to changes in the moisture content of the paste. It was also found that within the limits of the investigation, the fatigue characteristics of plain

concrete are apparently governed primarily by the fatigue characteristics of the cement paste.

The fatigue mechanism proposed for cement paste and plain concrete is basically the same and it is that fatigue failure occurs because small cracks form and propagate in the cement paste under repeated applications of loads less than the static failure load. The resulting crack pattern weakens the section to the point where it cannot maintain the applied load. The development of this damaging crack pattern depends primarily on the water-cement ratio of the cement paste and the presence of shrinkage stresses in the cement paste.

INTRODUCTION

Concrete technology has progressed to the point where the designer can design a concrete structure to perform satisfactorily during its service life. Unfortunately, however, enough is not known about concrete to permit the design of structures with very low factors of safety such as is done in the aircraft and spacecraft industries. Before such factors of safety can be used, it is necessary to know why concrete performs as it does.

One area of concrete technology that is lacking in knowledge of basic mechanisms is the area of fatigue of concrete. The general behavior of concrete under repeated loadings has been reasonably well established by numerous investigations, but the mechanism of fatigue is just beginning to receive attention.

To obtain a realistic design of a concrete structure that will be subjected to fatigue loading, it is necessary to know the exact effect, if any, of such things as the magnitude of the minimum load, the strength of the concrete, the composition of the concrete, the pattern of load cycles (same stress level or combinations of stress levels), and moisture conditions (dry, always wet, or rewetted). Knowing the expected number of cycles, the designer can then determine the maximum stress possible for his situation and then reduce this stress to a design stress by applying an appropriate factor of safety.

An understanding of the fatigue mechanism will enable an evaluation of the extent to which the various conditions previously mentioned affect the fatigue performance of the concrete. It may well be that only certain factors or conditions influence the fatigue performance and the work reported in this thesis had as its objective the determination of the mechanism which controls the fatigue of concrete.

SURVEY OF THE LITERATURE

The major part of this survey of literature was directed toward articles in the English language related to or on fatigue of concrete. Literature on fatigue of metals was also surveyed because it is in this area that considerable progress has been made towards an understanding of the nature of fatigue.

The information relating to metals is presented ahead of the information relating to concrete because it was felt that it provides a good background on fatigue behavior. A section on nomenclature has also been included so that the reader will be familiar with the terminology that appears throughout this thesis.

Nature of Fatigue

Fatigue is defined as the weakening and subsequent failure of a material resulting from a frequently repeated stress. This stress is further defined as that stress which is less than the ultimate strength of the material as determined from a static test. A distinct characteristic of fatigue is that the magnitude of the stress required to produce failure decreases as the number of cycles of stress increases.

Grover (1) in summarizing the current state of knowledge about the fatigue properties of structural materials (metallic and non-metallic) states that the process of fatigue is recognized as occurring in three phases:

1. Under successive cycles of stressing, cumulative damage occurs in some small region until a very tiny crack is produced.
2. Under additional cycles, this crack propagates until it becomes visible without magnification and then continues to grow until it has weakened the section.
3. After a few additional cycles, the specimen fractures.

Fatigue failure is shown by most metals and metallic alloys, by some plastics, by woods and plywoods, by ceramics, by mortars and concretes, and probably by other materials that have yet to be investigated with respect to fatigue. The information available on the various materials suffers from the disadvantage of being restricted to specific types of specimens, types of loading, environment conditions, etc., and thus it is sometimes difficult to draw comparisons. One feature that is apparent is that there are observable differences in the shapes of the S-N curves for the different materials. Mild steels are unlike most other materials in that they apparently can endure an infinite number of stress cycles if the magnitude of the stress is at or below a certain percentage of the static strength of the steel. On the other hand, concrete and most other materials will apparently fail if a sufficient number of stress cycles are applied even when the magnitude of the stress is quite small.

Most material properties can be reliably estimated by an average value of only a few observations, however, a material subjected to repeated loadings requires a number of observations because the effect of inhomogeneities is much more pronounced. Since the variability of observed values is very great, the fatigue life of a material can be realistically depicted only as a distribution of values for individual specimens and a reliable estimate of the fatigue life of the material is dependent on a statistical analysis of the test data.

Nomenclature

The nomenclature used by the early investigators when reporting their fatigue studies was not consistent. In 1949, the American Society for Testing and Material's Manual on Fatigue Testing (2) presented a standardized set of symbols and definitions. The nomenclature from this ASTM Manual that is applicable to this thesis is as follows:

Stress Cycle. - A stress cycle is the smallest section of the stress-time function which is repeated periodically and identically.

Nominal Stress, S. - The stress calculated on the net section by load/area without taking into account the variation in stress conditions caused by geometrical discontinuities such as holes, groves, fillets, etc. (For the purposes of this investigation "S" will be the percentage of the ultimate strength of the net section).

Maximum Stress, $S_{max.}$ - The highest algebraic value of the stress in the stress cycle, tensile stress being considered positive and compressive stress negative.

Minimum Stress, $S_{min.}$ - The lowest algebraic value of the stress in the stress cycle, tensile stress being considered positive and compressive stress negative.

Range of Stress, S_r. - The algebraic difference between the maximum and minimum stress in one cycle, that is,

$S_r = S_{max} - S_{min}$.

Mean Stress, S_m. - The algebraic mean of the maximum and minimum stress in one cycle, that is, $S_m = \frac{1}{2}(S_{max} + S_{min})$.

Stress Ratio, R. - The algebraic ratio of the minimum stress to the maximum stress in one cycle, that is, $R = S_{min}/S_{max}$.

Fatigue Life, N. - The number of stress cycles which can be sustained for a given test condition.

S-N Diagram. - A plot of stress against number of cycles to failure.

Fatigue Limit (or Endurance Limit), S_e. - The limiting value of the stress below which a material can presumably endure an infinite number of stress cycles, that is, the stress at which the S-N diagram becomes horizontal and appears to remain so.

Fatigue Strength, S_n. - The greatest stress which can be sustained for a given number of stress cycles without failure.

Figure 1 illustrates a fluctuating compressive stress and further explains, diagrammatically, some of these terms.

The S-N Diagram

A common way of representing fatigue test results is through the use of the S-N diagram. The stress, S, is plotted on the ordinary arithmetic scale and the number of cycles, N, may be similarly plotted. More commonly N is plotted on a logarithmic scale ("semi-log" plot).

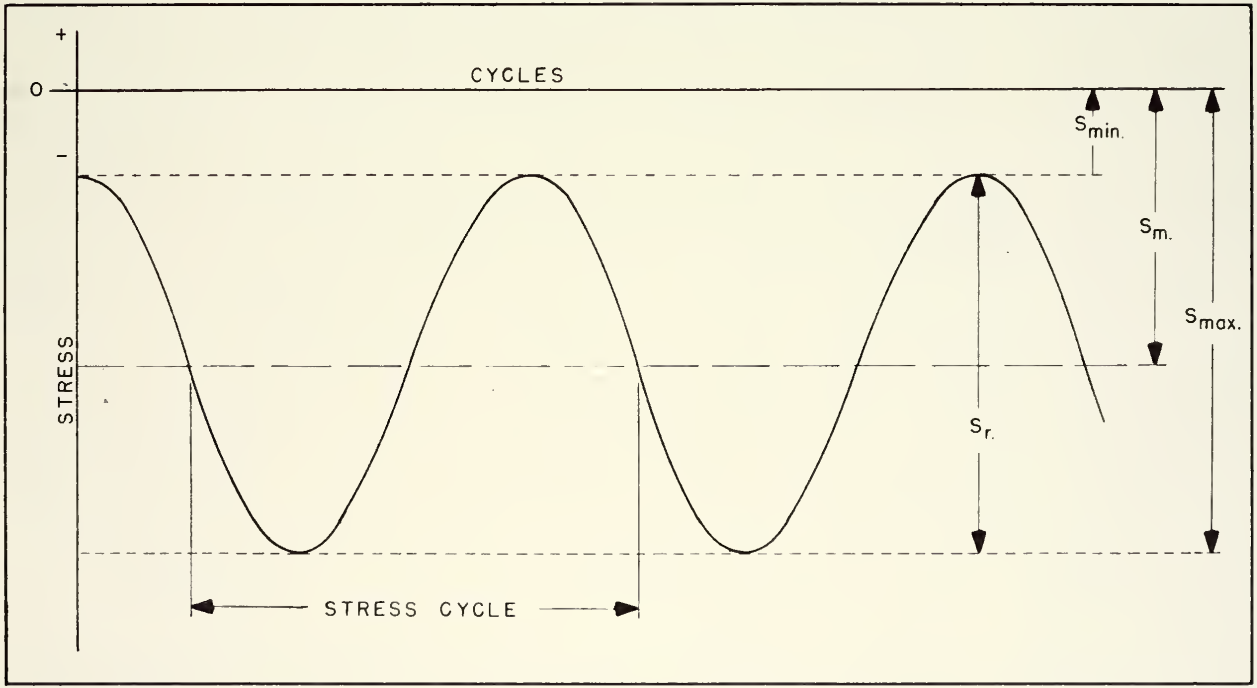

FIGURE I. TYPICAL FLUCTUATING COMPRESSIVE STRESS ENCOUNTERED IN FATIGUE TESTING

In addition, it is sometimes convenient to plot both stress and number of cycles on a logarithmic scale ("log-log" plot). Figure 2 illustrates the three types of S-N diagrams. An advantage of the semi-log and log-log methods of plotting is that by using the log scale for N the percentage of error is the same for both small and large values of N (3).

Fatigue Properties of Metals

Studies of the fatigue behavior of ferrous metals and ferrous alloys have been sufficient in number to permit the establishment of a number of well defined patterns which are characteristic of metals undergoing fatiguing action. On the other hand, fatigue studies related to concrete are small in number and since certain similarities have been observed between the fatigue behavior of concrete and some metals, such as the shape of the S-N curve, a knowledge of the behavior of the latter is helpful in understanding the behavior of concrete.

As stated earlier, the fatigue process is basically one made up of three stages: crack initiation, crack propagation, and final failure all at loadings less than that needed to cause a static failure. The current thinking is that crack initiation can be related to the behavior of dislocations in the crystalline lattice. Hardrath (4) states that with certain exceptions, the rate of crack propagation can be expressed in terms of the same factors which apply for crack initiation, that is, properties of the material, original configuration of the part, amplitude and mean stress levels, residual stresses present before the part is put into service, effects of changing load amplitude, and effects of temperature and chemical environment. One

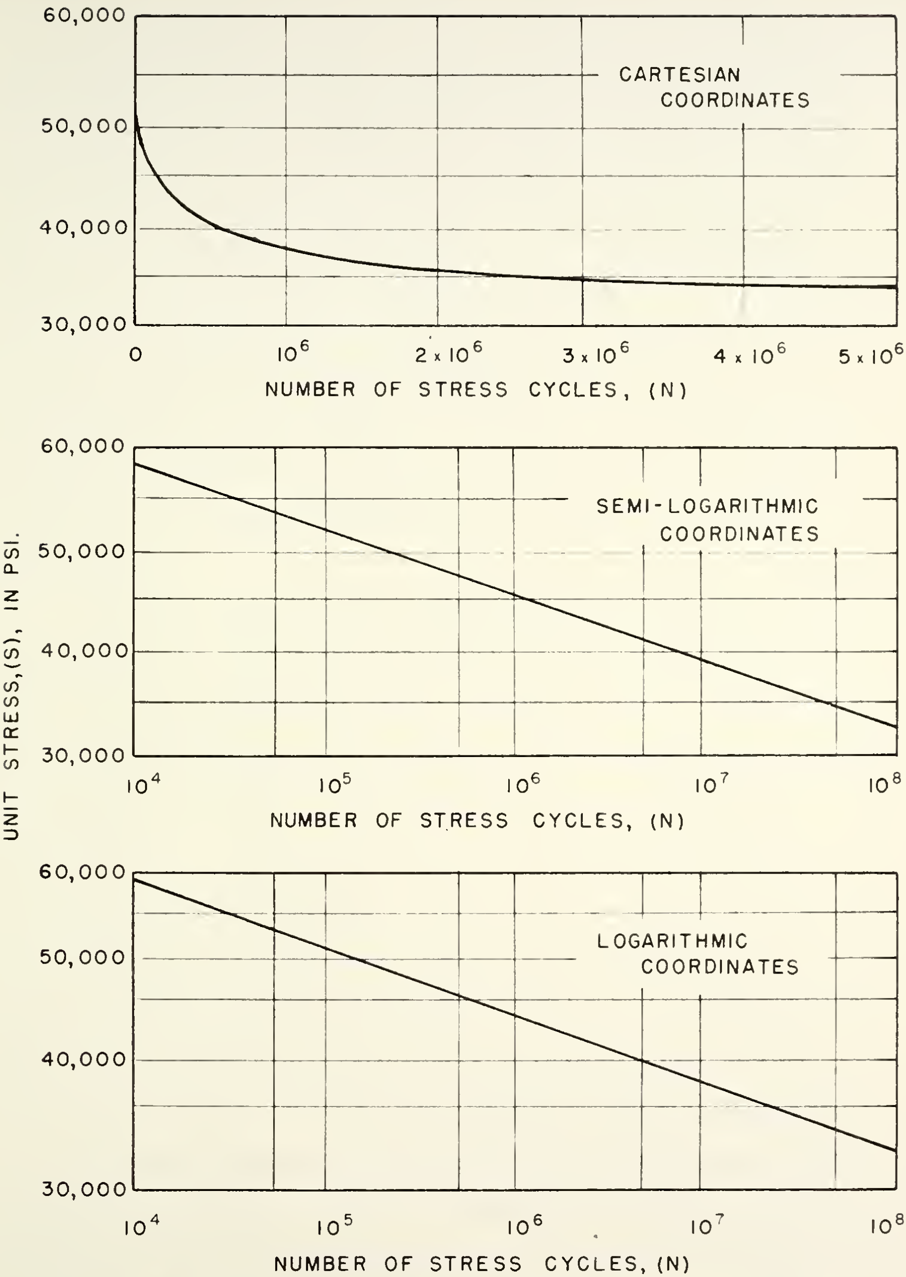

FIGURE 2. THE THREE TYPES OF S-N DIAGRAMS

of these exceptions is that the original geometry and stress concentration will gradually be replaced by the continuously changing configuration and stress distribution brought about by the growing crack. Another is that residual stresses present before the part was placed in service or introduced by high loadings prior to crack initiation will have been relieved by the crack progressing through the material in which they existed. Finally, consideration must be given to the dormant periods of crack growth that occur each time the applied load changes from a high to a low level. The last stage, final fracture, results when the reduced cross-section is too small to carry the applied load.

A number of fatigue failure theories have been proposed over the years and Gohn (5) reviews many of these along with a discussion of their merits and their disadvantages. Recently Wood (6) offered a theory in which he proposes the existence of two mechanisms to explain the shape of the S-N curve which is characteristic of relatively ductile metals. The first mechanism or H mechanism as he calls it is operative over the relatively steep, early portion of the S-N curve corresponding to the large amplitudes and short lives. The second mechanism or F mechanism is operative over the horizontal or progressively flattening portion of the S-N curve corresponding to small amplitudes and extended lives. Wood says that the H mechanism is a hardening mechanism and it is essentially one of unidirectional or static deformation. Fracture is produced by the piling up of dislocations at lattice obstacles. He considers the F mechanism to be a pure fatigue mechanism and that it produces nonhardening plastic strain, the result being structural deterioration due to the accumulation of point defects.

Until more progress is made in understanding the mechanism or mechanisms of fatigue of metals, one must depend on those features which have been brought forth by the numerous experiments that have been conducted during the past one hundred years. In many cases, the behavior of one metal is not the same as another. However, there are a number of features which are common to all metals. This basic nature of fatigue can be summarized from the many references reviewed as follows:

1. Ferrous metals and ferrous alloys have a definite fatigue limit, that is, the S-N curve for these materials becomes practically horizontal. This fatigue limit is generally about 50 percent of the ultimate tensile strength.
2. Most nonferrous materials have no definite fatigue limit and the fatigue strength must be reported in terms of both a stress and the number of cycles endured at that stress.
3. Flaws or discontinuities either on the surface or in the interior of a piece have a detrimental effect on the range of stress which may be withstood for a given number of cycles.
4. Speed of testing and temperature under normal conditions have little, if any, effect on the fatigue strength of metals, except under special conditions. High temperature is one of these special conditions.
5. If a ferrous metal is repeatedly stressed just below its fatigue limit (understressing), it may gain strength. Then

when tested at a higher stress, its fatigue life is generally longer than the fatigue life of a virgin piece initially stressed at the higher level.

6. If a ferrous metal is repeatedly stressed above the fatigue limit short of failure (overstressing), it will ultimately fail when tested at a stress below the fatigue limit.
7. At a given fatigue life the range of stress necessary to produce failure usually decreases as the mean stress is increased.

In recent years fatigue investigations have been more exacting and as a consequence conditions which previously had been ignored are now being checked for the extent of their influence. As an example, it was only recently that investigators realized that variations in the relative humidity of a normal laboratory atmosphere can have a very significant influence on fatigue test results. Bennett (7) conducted fatigue tests on aluminum alloys and magnesium alloys in an environmental chamber and found that the S-N curve for a material tested in a high humidity atmosphere lies below the S-N curve for the same material tested in a low humidity atmosphere.

Fatigue Properties of Concrete

The present understanding of the fatigue behavior of concrete is based almost entirely on exploratory research which in most cases was conducted for the sole purpose of getting an answer to a specific problem. For this reason it is often difficult to make a general evaluation from information obtained because widely different procedures (manufacturing of specimens and testing of specimens) have been used. To further complicate matters, information pertaining to the fatigue properties of concrete should be divided into three catagories according to the type of concrete. These three types of concrete are: plain concrete, reinforced concrete, and prestressed concrete.

Information on the fatigue properties of plain concrete is the most plentiful, and it has been extensively reviewed by this writer (8) and by Nordby (9). Nordby, in his review, also covered reinforced concrete and prestressed concrete. Since this study is concerned only with the fatigue properties of plain concrete and specifically the mechanism of fatigue in cement paste and plain concrete, the reader is referred to Nordby's review for a summary of the current knowledge of the fatigue properties of reinforced concrete and prestressed concrete. The review of recent investigations of the fatigue behavior of plain concrete will be presented in two parts. The first part will cover general investigations of the nature of fatigue of concrete and the second part will cover those investigations which were directed toward a better understanding of the mechanism of fatigue in concrete.

General Investigations

This writer (8) conducted axial-compression fatigue tests on air-entrained and non-air-entrained plain concrete cylindrical specimens, 3 inches in diameter by 6 inches in height, at specific stress levels at a speed of 1000 cycles per minute. This study indicated that the fatigue behavior of non-air-entrained and air-entrained plain concrete is not significantly different. This conclusion must be modified as follows: it pertains to oven-dried specimens that were cured under water for 28 days prior to drying and both concrete mixes were designed for a strength of 4000 psi (water-cement ratio of 0.69 by weight for the non-air-entrained mix and 0.61 for the air-entrained mix). Also observed in this study was that the air-entrained concrete was more uniform than the non-air-entrained concrete with regard to both fatigue and static strength properties. In addition, there was no evidence of any fatigue limit for the concretes, at least in the neighborhood of 10 million repetitions of loading.

Gray (10) using the same size cylindrical specimens and the same fatigue testing machine, tested two different lightweight-aggregate concretes, one proportioned for a high strength (6300 psi) and the other for a relatively low strength (3800 psi). As in the previous study, the test specimens were cured in water for 28 days and then oven dried. This study indicated that the fatigue behavior of high strength lightweight concrete is similar to that of low strength lightweight concrete and that the fatigue behavior of the lightweight aggregate concrete is not significantly different from that of the normal-weight concrete previously discussed. In addition, it was noted that there is no evidence of a fatigue limit for lightweight aggregate concrete in the neighborhood of 10 million repetitions of loading.

Hilsdorf and Kesler (11) investigated the influence of rest periods and the effect of variations in the loading. Test specimens were 6- by 6- by 64-inch plain concrete beams (water-cement ratio of 0.52) which were wet cured for 7 days and then air dried before being subjected to repeated bending loads. They concluded first that the fatigue strength of plain concrete subjected to repeated bending loads increases with the introduction of periodic rest periods. This beneficial effect was found to be a function of the length of the rest period when the length is less than 5 minutes, however, further increases in the length of the rest period from 5 to 27 minutes did not affect the final result. They concluded further that the fatigue strength of concrete subjected to repeated loads of varying magnitude is influenced by the sequence in which these loads are applied. The total number of cycles to failure was found to be higher for $S_1 > S_2$ than for $S_1 < S_2$. Finally, Hilsdorf and Kesler stated that the Minor hypothesis gives nonconservative values of the fatigue strength of concrete under high loads and conservative values for low loads. (The Minor hypothesis states that each series of stress cycles accounts for a certain fraction of the total fatigue damage, and when these fractions add up to unity, failure will occur. The mathematical expression for this theory is $\sum \frac{n_i}{N_i} = 1$ where n_i is the number of cycles actually endured at a particular stress level and N_i is the fatigue life at that same stress level.)

Not many general conclusions can be drawn regarding the fatigue of plain concrete since an analysis of the results of the investigations conducted to date shows that the methods of investigating the problem varied considerably. Loading arrangement, rate of loading, type and size of specimen, and age of specimen are only a few of the differences existing between investigations. However, certain generalized statements can be made as follows:

1. Early investigations indicated that the fatigue limit of plain concrete, whether subjected to repeated compressive loads or flexural loads, appeared to be about 55 percent of the corresponding ultimate static stress. On the other hand, more recent investigations indicate that plain concrete does not possess a fatigue limit, at least within 10 million repetitions of load.
2. Rest periods seem to increase the fatigue life of concrete.
3. Age and curing appear to have a significant effect on the fatigue strength of concrete.
4. Speed of testing, at least from 70 to 1000 cycles per minute, has little effect on the fatigue strength of concrete.

Mechanism Investigations

In the United States, research directed towards an understanding of the mechanism of fatigue failure in concrete has been conducted at the University of Illinois. Murdock and Kesler (12) studied the effect of coarse aggregate by inserting single, preshaped limestone aggregates in the tension zone of mortar flexure specimens. The mortar specimens (water-cement ratio of 0.63) were 4- by 2- by 42-inch beams and they were tested in an air-dried condition. The result of this study was the presentation of the following hypothesis:

"The initiation of fatigue failure may reasonably be attributed to the progressive deterioration of the bond between the coarse aggregate and the binding matrix together with an accompanying reduction of section of the specimen.

"The final failure of the specimen occurs by fracture of the matrix. This fracture may be progressive, occasioned by the gradual deterioration of the paste-fine aggregate bond, if the remaining section is sufficient to withstand the applied load. If the section is so reduced that the ultimate strength of the matrix is attained the final fracture will be almost instantaneous.

"The failure may be wholly associated with the matrix in low-cycle fatigue failures if the residual shrinkage stresses or stress concentrations occasioned by the shape of the aggregate or its proximity to adjacent aggregate or to a free surface are significant.

"The bond stresses may be intensified if the modulus of elasticity of the coarse aggregate exceeds that of the binding matrix, if it is assumed that a section is subjected only to flexural stresses. The varied shape and orientation of coarse aggregate in typical concrete precludes the development of flexural stresses alone; the shearing stresses which are present may modify the behavior of the matrix somewhat. In any case, if the elastic modulus of the aggregate is greater than that of the paste there should be reasonable assurance of a preferential failure at the aggregate-matrix interface. The same condition, should it exist within the matrix would similarly affect the paste-fine aggregate bond."

Doyle, Kung, Murdock, and Kesler (13) extended the work carried out by Murdock and Kesler by studying the behavior of the cement-fine aggregate matrix with the inclusion of various preplaced coarse aggregates and also the behavior of the matrix with a preformed void. Specimen condition, size, etc., were the same as in the earlier study, however, this time the aggregates were cylindrical pieces of aluminum or granite. The preformed void was dimensionally the same as the natural aggregate cylinders. They concluded that (a) residual stresses due to shrinkage of mortar around a single, comparatively rigid, unbonded inclusion have no significant effects on either static or fatigue strength and (b) static and fatigue failures initiate in the bond between the coarse aggregate and the mortar matrix when the modulus of elasticity of the aggregate is greater than that of the matrix.

Neal, Kung, and Kesler (14) increased the complexity of the models used by Doyle et al., so that they could examine the effects of more than one particle of coarse aggregate in close proximity to each other. Specimen condition, size, etc., were the same as in the earlier studies except that all the testing was conducted on saturated specimens. Aggregate pieces were again cylindrical and were either of granite or limestone. The conclusions were: a) fatigue failure begins in the bond between the coarse aggregate and the mortar matrix and is not influenced by the elastic modulus of the coarse aggregate (this latter is in contradiction with the conclusions of the two previous studies) and b) residual stresses due to shrinkage of the mortar matrix around particles of coarse aggregate do not occur to an extent great enough to influence either the static or fatigue strength of the specimen, or to influence the plane of failure.

Glucklick (15) investigated the mechanics of the propagation of fatigue cracks in mortar beam specimens. Specimen size and the water-cement ratio were the same as used in the previously mentioned studies. Notched and unnotched beams were used to determine stress-strain characteristics during fatigue life. Measured strains were interpreted in terms of crack lengths, the correlation between compliance and crack length having been pre-determined in static tests. The product of the critical crack length and the square of the maximum stress proved to be a constant number for either unnotched beams or notched beams with approximately equal notch depths. Glucklich noted that the material had the same criterion of fracture in both fatigue and static loadings, namely, the strain-energy release rate.

In summary, it can be said that a start has been made towards understanding the basic nature of fatigue of concrete and apparently one of the mechanisms that operates in the fatigue of concrete is the failure of the bond between the mortar and the coarse aggregate.

PURPOSE AND SCOPE

The purpose of this research is to describe the mechanism by which plain concrete fails in fatigue and to explain the observed results in terms of the mechanism postulated.

Since concrete is a composite material, it can be given different characteristics by changing the type and/or the amount of its ingredients. For many purposes, concrete can be broken down into two major components: the cement paste and the aggregate. It is an established fact that both the cement paste and the aggregate will influence the static strength properties of plain concrete and for that reason this research is concerned first with the fatigue behavior of cement paste loaded in axial compression and then the effect on the fatigue characteristics when the paste is diluted with aggregate.

The fatigue behavior of cement paste could be investigated with respect to a number of variables, however, it is most likely that only three things are of major importance. These three are the effect of the structure of the hardened paste, the effect of its moisture content, and the stress level at which the fatigue tests are conducted.

The structure of hardened cement paste is an open, capillary one for high water-cement ratios. When the water-cement ratio is low, the paste structure is dense. To obtain a paste with an open capillary structure, a water-cement ratio of 0.70 by weight was selected and to obtain one with a dense structure, a water-cement ratio of 0.45 by weight was selected. A ratio lower than 0.45 would have meant difficulties in the casting of specimens.

The static strength properties of cement paste change as it dries out, therefore an investigation of the fatigue properties of the cement paste at more than one moisture content was thought highly desirable since two investigators (14, 16) noted that the fatigue behavior of saturated mortar was apparently different from that of air-dried mortar. Moisture contents of 100 percent of saturation and approximately 95 percent of saturation were chosen to insure usable test specimens. An uncracked low water-cement ratio cement paste specimen of the type used in this study having a moisture content of about 90 percent of saturation or below is difficult to obtain.

The stress level at which fatigue tests are conducted is extremely important for all materials since the number of fatigue cycles that can be endured at a given stress level is a function of the magnitude of the stress level. As with all fatigue tests time becomes an important factor, therefore, the higher stress levels (percent of the ultimate static compressive strength of the material being tested) were chosen so as to permit a greater accumulation of data.

The information gained from the testing of the hardened cement paste, along with other known properties of cement paste and similar brittle materials are then brought together to develop a hypothesis on the mechanism of fatigue in hardened cement paste.

The introduction of aggregate into cement paste raises two important questions regarding fatigue behavior. Do the fatigue characteristics of the concrete differ from those of the paste is one of the questions and what is the effect of aggregate type is the other question. It seems reasonable to assume that these two questions are important ones because, for an example, concrete, in contrast to cement paste, undergoes considerably less volume change when its moisture content is changed.

The influence of the aggregate on the fatigue characteristics of the cement paste was investigated by testing concrete made by diluting the high and low water-cement ratio pastes with identical amounts of the same aggregate. The resulting concretes were then tested at moisture contents similar to those selected for the undiluted pastes. Because concrete is less susceptible to major shrinkage cracking, additional moisture content levels were obtained by air drying specimens for five weeks and by oven drying specimens.

The effect of the aggregate type on the fatigue behavior involves a consideration of the strength of the aggregate and also a consideration of the surface characteristics of the aggregate (chemical and physical).

The investigation of the effect of the aggregate strength was accomplished by combining each of the two water-cement ratio pastes with aggregates whose strengths were either weaker or stronger than the strengths of the undiluted pastes. Since aggregate strength was the variable under consideration, it was essential to control the surface characteristics of the aggregates used. Since it is difficult to find natural aggregates that are homogeneous and chemically and physically alike except for strength, the aggregates for this part of the research were manufactured. The manufacturing process was simply one of crushing hardened cement pastes of known strengths.

The specific effect of the surface characteristics was not investigated although an attempt was made to compare angular crushed aggregate with rounded aggregate. A scheme was devised for rounding the crushed aggregate, but it turned out to be a very time consuming process because it was extremely difficult to remove all traces of fractured surfaces.

Drawing upon the information gained by testing the different concretes at various stress levels and moisture contents, and what is known about the paste itself, the physical properties of the aggregates, the strength properties of the various concretes, and various failure theories for brittle materials, a hypothesis is offered on the mechanism of fatigue in plain concrete.

FATIGUE OF CEMENT PASTE

The objective of this part of the investigation was to establish S-N curves which would indicate the existence of any differences in the fatigue behavior of hardened cement pastes. The water-cement ratio of the paste and the moisture content of the paste were the two variables considered.

Design of the Experiment

Fatigue test results are commonly stated as a function of the static strength of the material, therefore, there is the problem of estimating the strength of the test specimen by some practical method. Exploratory work resulted in a procedure for making specimens which permits a close estimate of the unconfined static compressive strength of the test specimen scheduled for fatigue testing. This procedure involved the making of one specimen at a time and successive specimens in an identical manner. The result of this manufacturing procedure was a low mix to mix variation for a given mix design and, because of this ability to keep the strength coefficient of variation of each mix design at a practical minimum, it was decided that a minimum of five specimens would be tested in fatigue at any given stress level. An additional justification for this decision was that the research was directed towards the establishment of specific fatigue characteristics of cement paste, rather than the establishment of S-N curves suitable for use in design. This procedure of making one specimen at a time gave the added advantage of being able to test each specimen at the same age, since specimens could be made daily with comparative ease in contrast to the time consuming procedure of making a large number of specimens on a periodic basis.

The procedure used was to make two specimens each day, allow them to cure for 28 days and then immediately perform the required static or fatigue test. In those cases where a specimen was to be tested at a moisture content of less than the saturation moisture content, drying was started at the age of 28 days and immediately after a specified drying time, the specimen was tested statically or in fatigue. Air drying was selected as the drying method since oven drying meant the introduction of higher temperatures and a possible alteration of the chemical structure of the cement paste.

Specimen size was selected as 2 inches in diameter by 4 inches high because the load capacity of the fatigue testing machine restricted the cross-sectional area of the low water-cement ratio paste specimens.

Obtaining a homogeneous cement paste specimen with an open capillary structure was not an easy task. The 0.70 water-cement ratio used resulted in an extremely fluid mixture that did not harden in time to prevent a change in the concentration of cement particles from top to bottom in the 2-inch diameter by 4-inch high mold. Various procedures to induce homogeneity were tried and discarded. Among these were a) the use of calcium chloride as an accelerator to induce rapid set and b) slow speed, end for end rotation of the specimen commencing immediately after casting. The procedure finally selected was that of using the bottom four inches of a 2-inch diameter by 12-inch high cylinder for use as a test specimen. This procedure was adopted after density and strength determinations made on samples taken from various levels in specimens whose overall heights varied from 4 to 12 inches indicated that the bottom 4 inches of a 12-inch high specimen is apparently homogeneous.

Since it was desirable to have the high and the low water-cement ratio pastes similar in every manner except for those characteristics associated with the particular water-cement ratio, the 0.45 water-cement ratio pastes were also cast in a 2-inch diameter by 12-inch high mold. As with the 0.70 w/c paste specimens, the bottom four inches were used as a test specimen.

Specimen Fabrication

The 0.70 water-cement ratio paste specimens and the 0.45 water-cement ratio paste specimens were manufactured in as nearly an identical manner as was possible.

Materials

The only materials used in this part of the investigation were city tap water and Type I portland cement manufactured in central Indiana and from a single clinker batch (laboratory designation 316). Because the cement was from one lot, it was assumed that its characteristics did not vary significantly. The chemical and physical characteristics of the cement are shown in Table 1.

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT 316

Physical Properties

Fineness, No. 325 sieve	93.6 percent
Specific Surface, Blaine	3320 sq. cm. per gm.
Initial set	3 hr. 20 min.
Final set	5 hr. 20 min.
Air Entrained (ASTM Designation: C185-59)	6.6 percent

Chemical Analysis

Compound	Percentage present
Silicon dioxide, SiO_2	22.01
Aluminum oxide, Al_2O_3	5.38
Ferric oxide, Fe_2O_3	2.15
Calcium oxide, CaO	65.40
Magnesium oxide, MgO	0.75
Sulphur trioxide, SO_3	2.47
Loss on ignition	1.25

Calculated Compound Composition

Compound	Percentage present
Tricalcium Silicate, C_3S	49.45
Dicalcium Silicate, C_2S	25.87
Tricalcium Aluminate, C_3A	10.60
Tetracalcium Aluminoferrite, C_4AF	6.54
Calcium Sulphate, $CaSO_4$	4.20

Mixing

The necessary quantity of cement for each cylinder cast was obtained by weighing out the same amount of cement each time a cylinder was made. The necessary quantity of water was obtained from a container which dispensed volumetrically the same weight of water each time. These containers, one for the 0.70 w/c mix water and one for the 0.45 w/c mix water, were specially made for this investigation, and they can best be described as being custom made transfer pipettes of sufficient size to contain the required weights of mix water. Two precautions had to be taken to insure that the containers dispensed the same weight of water each time. The tap water was allowed to run until its temperature dropped to that of the main water lines (this was essentially constant) and the container had to be filled with care so as to prevent the entrapment of air. The cement and water were first hand stirred until the two were indistinguishable. The mixture was then mixed in a Hobart electric mixer (Model N-50) for one minute. The 0.70 w/c mix was mixed at speed 2 for the full minute, while the 0.45 w/c mix was mixed at speed 2 for thirty seconds and at speed 3 for the remaining thirty seconds. The conventional rounded bottom bowl and the wire loop whip in combination with the mixing speeds used, insured a thorough blending of the cement and the water.

Casting

Casting was done in two specially built brass molds that were manufactured from brass tubing and brass plate. The brass tubing was split and then the bottom 4 1/2 inches was machined to give a constant inside diameter of 2 inches. All abutting surfaces of the mold were coated with Dow Corning high vacuum grease to eliminate any leakage of the mix water from the molds. The casting procedure for the 0.70 w/c mix was simply one of pouring the mix into the mold. The 0.45 w/c mix was pourable, but not quite as fluid as the 0.70 w/c mix, so to insure the removal of entrapped air the sides of the mold were tapped a few times with a hard rubber mallet.

Curing

Immediately after casting, the molds were covered to reduce the loss of water by evaporation. The specimens were stored in the molds for 24 hours at room temperature and were then removed from the molds and stored for 27 days in a saturated lime solution having a temperature of 75°F.

Test Specimen Preparation

Prior to reaching an age of 28 days, the 2-inch diameter by 12-inch high cylinders were removed from the saturated lime solution for a period just long enough to perform the operations necessary to produce the 2-inch diameter by 4-inch high test specimens and their accompanying middle portion specimens. The first part of this operation was to make three saw cuts through the specimen perpendicular to the vertical axis of the 12-inch high cylinder. The sawing was done with a masonry saw and the cuts were placed 4, 5, and 9 inches from the bottom of the cylinder. After sawing, the ends of the test specimen and the middle specimen were ground with size 240-B Alundum abrasive grain to obtain smooth, parallel surfaces. Although these operations were not conducted under water, they were conducted in a manner which kept the specimens continuously wet.

The saturated specimens that were tested statically were maintained in the saturated condition during the compression test by wrapping each specimen with a wet cloth. The saturated specimens tested in fatigue were kept wet by first wrapping each specimen with wet absorbent cotton. The cotton-wrapped specimen was in turn wrapped with polyethylene film which was secured at each end of the specimen by rubber bands. Normally 24 hours was the longest a specimen would remain in the fatigue testing machine and this wet cotton method was found to be very effective in keeping the specimen wet for periods in excess of 24 hours.

Specimens that underwent air drying were tested statically right after the air drying period was completed. Air-dried fatigue test specimens were also tested immediately, but the specimens were wrapped with polyethylene film which was secured at each end by rubber bands in an effort to prevent any additional loss of moisture during the testing. The appearance of these wrapped specimens immediately after failure suggested that this method was quite successful in keeping moisture from leaving the specimen during the duration of the test.

Air drying was accomplished by putting the specimens in a closed room which stayed at a relatively constant temperature ($77 \pm 2^{o}F$) and a relatively constant relative humidity ($52 \pm 4\%$). The specimens were placed in this room at the age of 28 days and were removed from the room after a specified period which was long enough to reduce the water content of the specimen to the desired level. In an effort to control shrinkage stresses produced by the loss of water, the ends of the specimens were covered with molding clay for the duration of the air drying. The purpose of this procedure was to confine the resulting moisture gradients to radial directions.

The drying period used for the 0.70 w/c paste specimens was 4 1/2 hours, the resulting water content being approximately 96 percent of that at saturation. The drying period for the 0.45 w/c paste specimens was 3 days and the resulting water content was approximately 91 percent of that at saturation. So there will be no misunderstanding, it is pointed out at this time that the saturated condition referred to is the moisture content of the specimen at the time of removal from the curing water. The degree of saturation for each specimen was calculated from the weight of water lost during air drying and the estimated additional water loss if the specimen had been oven dried at 220°F to constant weight after completion of the air drying. The estimate of the additional water loss was based on the measured water loss of a number of representative specimens. A number of 0.45 w/c paste specimens were air-dried for 6 days, but this phase was terminated because most of the specimens suffered considerable surface cracking.

Static Compression Tests

The purpose of the static compression tests was to establish a reliable estimate of the strengths of the two cement paste mixes. A reliable estimate of a particular grouping of specimens was essential since it was these particular estimates that established the magnitude of the fatigue loads.

Procedure

Saturated specimens were tested at the age of 28 days for their unconfined compressive strength. Air-dried specimens were tested right after completion of their drying period. These static compression tests were performed in a 50,000 lb. capacity Riehle screw-type testing machine modified by the addition of a Graham variable speed drive. The no-load head speed of the testing machine was set at 0.05 inches per minute as specified in ASTM Designation C 39-61.

Analysis

The static strength data for both the 0.70 and 0.45 water-cement ratio pastes are presented in Tables 8 and 10, Appendix A. Many comparisons of these data could be made but only those pertinent to the present investigation will be discussed. It should be noted that the number of specimens tested for any given condition is not constant and also that "operators" change. These factors should be considered in any analysis of the data.

The strength data for the 0.70 water-cement ratio paste mix are summarized in the following tabulation where S is the approximate degree of saturation, n_1 is the number of test specimens, $\overline{Y}_1$ is the average compressive strength of the test specimens, C_1 is the coefficient of variation for the test specimen strengths, and n_2, $\overline{Y}_2$, and C_2 are the corresponding values for the middle specimens.

Operator	S (%)	n_1	$\bar{Y}_2$ (psi)	C_1 (%)	n_2	$\bar{Y}_2$ (psi)	C_2 (%)
A	100	31	3652	7.0	8	3124	4.9
B	100	9	3734	10.1	29	3286	5.7
C	100	14	3248	3.1	19	3237	3.6
C	96	6	3538	4.3	19	3325	3.6

These data suggest that operators A and B made their specimens in a similar manner, therefore, an analysis was performed to determine if this data could be pooled to permit a better estimate of the paste strength. The analysis involved an evaluation of the variances of the two groupings and then an evaluation of the means of the two groupings (see Table 24, Appendix C for the calculations). An F-test at an α-level of 0.05 resulted in the acceptance of the hypothesis that the population variances were equal and a t-test at an α-level of 0.05 resulted in the acceptance of the hypothesis that the population means were equal, hence it was decided that a pooling of the data was justifiable. Operator C apparently made his specimens in a manner different from that of operators A and B, and an analysis of the data confirms this observation (see Table 25, Appendix C). Reference has been made to the operator who made the specimens because this is the only assignable cause of the differences. All operations, other than making the specimens, were performed by operator C.

The strength data for the 0.45 water-cement ratio paste mix are summarized in the following tabulation:

Operator	S (%)	n_1	$\bar{Y}_1$ (psi)	C_1 (%)	n_2	$\bar{Y}_2$ (psi)	C_2 (%)
B	100	11	9228	4.0	11	8206	16.2
C	100	17	9630	3.7	40	9724	2.7
C	91	6	10878	2.6	21	11117	3.1
C	87	4	11042	5.6	5	10922	9.0

These data suggest that there was a difference between operators. The strength data for specimens made by operator B have been included because they show quite clearly the result of inconsistencies in making the specimens. These specimens were made at the end of operator B's employment, therefore, the decision was made to disregard the cylinders he had made and have all the 0.45 w/c paste specimens made by the same operator. Very little strength data is shown for the 6-day air-dried specimens (87 percent of saturation) because a number of these specimens failed at abnormally low loads when tested statically in compression. These abnormal failures were attributed to shrinkage cracking which appeared on the specimens prior to completion of the 6-day drying period.

Results

Those characteristics of the two cement pastes which formed the basis for the analysis of the fatigue data are summarized in the following tabulation:

Uncorrected w/c	S (%)	n_1	$\bar{Y}_1$ (psi)	C_1 (%)
0.70	100	40	3671	7.7
	100	14	3248	3.1
	96	6	3538	4.3
0.45	100	17	9630	3.7
	91	6	10878	2.6

In addition to the preceding, consideration of the data obtained from testing the middle specimens suggests the following statements:

1. Apparently the average compressive strengths shown in the preceding tabulations are reliable estimates since the middle-specimen strengths do not indicate any gross differences among companion pieces and among groupings.
2. The 0.45 w/c paste mix gained considerably more in strength when air-dried than did the 0.70 w/c paste mix.

Fatigue Tests

Since the objective of this part of the investigation was the determination of the fatigue characteristics of cement paste with respect to the effect of certain variables rather than the establishment of a S-N curve, it was not deemed necessary to conduct the testing at numerous load levels. Previous investigations (8, 10) in which a fluctuating compressive load was used indicate that the S-N curve is apparently a straight line, therefore, it was felt that adequate information could be obtained by testing only at two or three stress levels.

In this investigation it was felt that the method of making the specimens provided the necessary control of the strength properties to permit a close estimate of the true stress level in a given specimen undergoing fatiguing action.

Procedure

The fatigue tests were normally conducted at stress levels which insured that a particular specimen would endure at least 1000 cycles and would fail before one million cycles. The first condition was necessary because it sometimes took as many as 300 cycles to verify the magnitudes of the applied loads. The latter condition was necessary because conflicts with other active projects in the laboratory prevented any long time testing.

The magnitude of the minimum load was controlled by the operating characteristics of the fatigue machine. It was necessary to maintain some minimum load or there would have been an impact loading in every full cycle.

The magnitude of the maximum load was based on the average static compressive strength of at least five specimens from the particular grouping. The range in stress levels was not the same for every series of tests. For some, the highest stress level was 80 percent of the estimated compressive strength of the particular grouping, for others it was 70 percent. The stress levels varied in increments of 10 percent for each series of tests and the lowest stress level used was 40 percent.

The process of establishing the desired maximum and minimum loads on the fatigue testing machine required a considerable number of cycles, therefore, the loading was set by first inserting a dummy specimen in the machine. When the loads were established, the machine was stopped and the dummy specimen was replaced by a test specimen. Upon restarting the machine, the only task to perform was that of verifying the magnitudes of the loads and this could be done quickly and easily.

All the fatigue tests were started at the age of 28 days for the saturated specimens and right after the completion of drying for the air-dried specimens. In every case, a virgin specimen was used to obtain the information that is reported in this thesis. If a test was interrupted for any reason, it was started over again with a new specimen.

In those cases where a specimen had not failed by the time the fatigue machine had to be shut down, it was immediately tested statically.

The Krouse-Purdue Fatigue Testing Machine

The Krouse-Purdue axial-load fatigue machine that was used in this study is shown in Figure 3. It is of the constant deflection type and derives its force from hydraulic pressure acting on a large piston directly connected to the test piece through a piston rod.

The load applied by the machine consists of two components: a preload and a pulsating load. The preload is directly proportional to the average differential pressure existing between the two ends

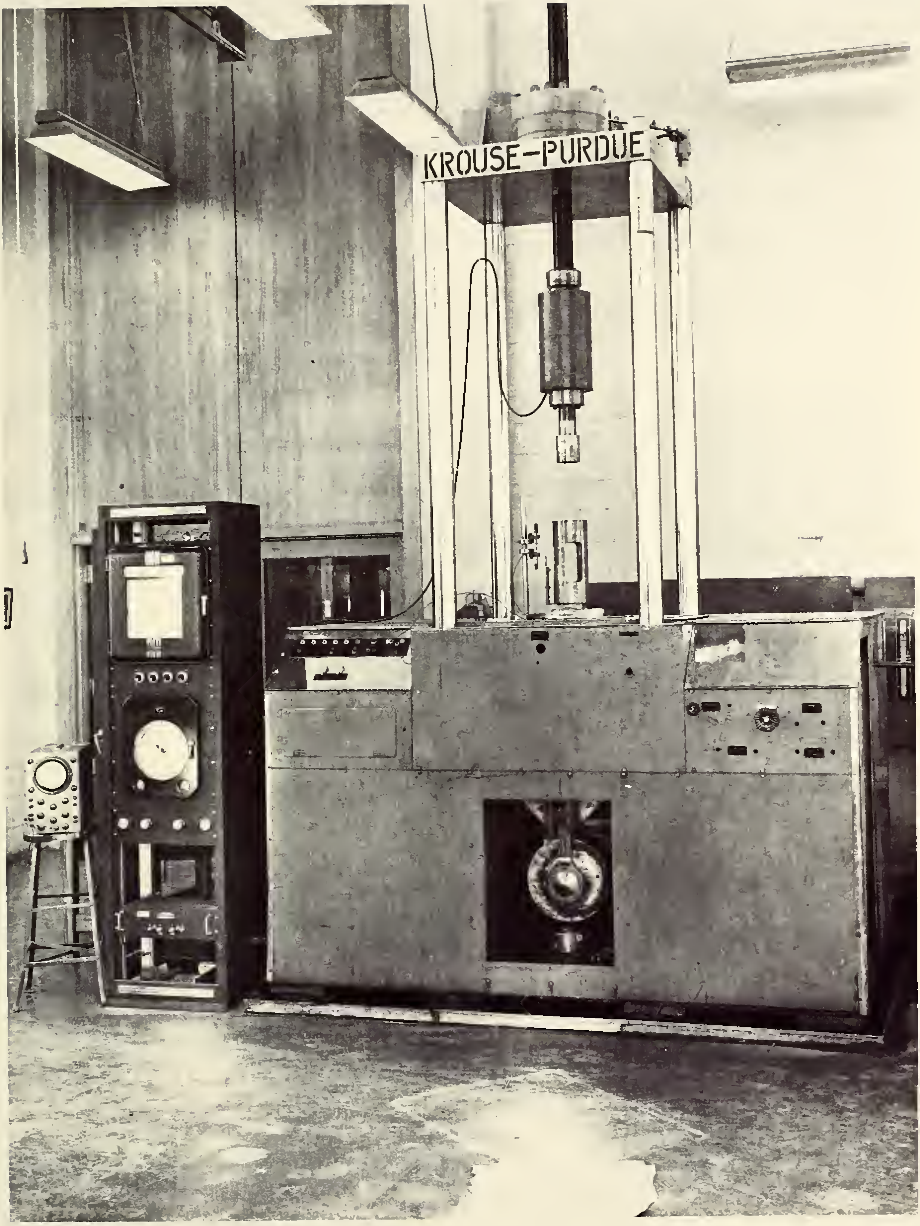

FIGURE 3. GENERAL VIEW OF FATIGUE MACHINE

of the hydraulic cylinder, and it is controlled by automatically controlling make-up oil pressures. The amount by which the pulsating load varies above and below the preload depends on the throw of a variable-throw crank that can be adjusted before or while the machine is operating. The deflection characteristics of the specimen, the specimen holder, the load screw, and the piston rod also influences the magnitude of the pulsating load. Figure 4 is a simplified line diagram of the hydraulic system of the machine.

Holding the specimen in place is a load screw which extends through the top head of the machine. This load screw may be adjusted for the required testing space by means of a reversible motor driving a rotating nut. When the desired screw setting is reached, a clamping nut is closed on the screw by means of a hydraulic cylinder. This action prevents an end motion of the screw when acted upon by the testing force.

The machine has a capacity of ± 60,000 lbs. and operates at 1000 cycles per minute. Loads are measured to within ± 100 lbs. by an electronic system that is actuated by a Baldwin-Lima-Hamilton type U-1, SR-4 load cell which is an integral part of the load screw.

Specimen Behavior

There was no discernible difference in the type of fracture that occurred for the statically tested specimens and the fatigue tested specimens. The type of failure for the 0.70 mix specimens was essentially the "cone" type of failure which frequently results when concretes are tested in compression. The type of failure for the

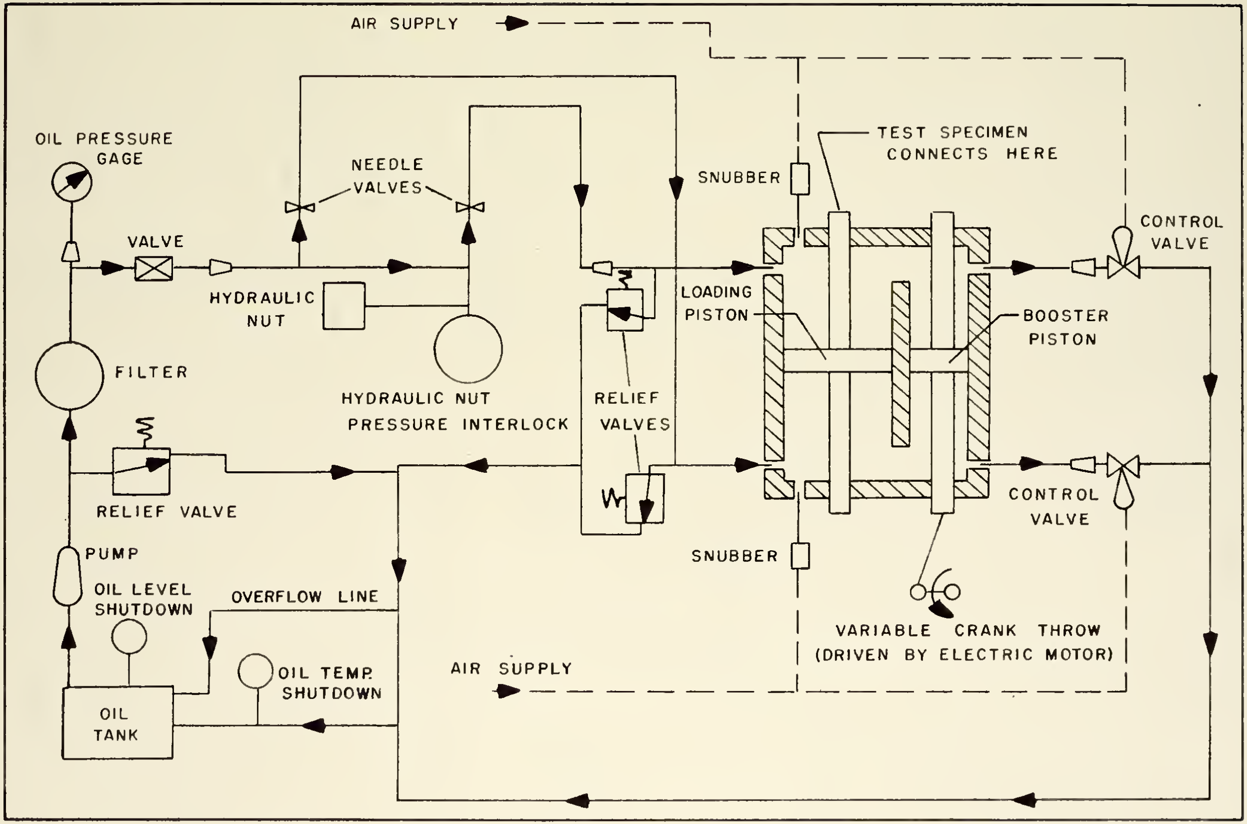

FIGURE 4. HYDRAULIC SYSTEM OF FATIGUE MACHINE

0.45 mix specimens was the "splitting" type of failure (17), the specimens literally "exploding" at failure.

Occasionally it was possible to monitor the instruments that measured the fatigue loads for part or all of a test. Since the fatigue machine is of the constant deflection type, any permanent shortening of a specimen results in an increase of the stroke of the load piston and consequently the loads on the specimen are changed, the maximum load decreasing and the minimum load increasing.

One of the instruments in the load measuring system of the fatigue machine was a cathode-ray oscilloscope which, when used in conjunction with manual operation of the load indicating instrument, permitted the operator to follow continuously the changes in the loading on a particular specimen. However, because of the design of the load measuring system, it was impossible to monitor the maximum and minimum loads simultaneously, hence in the discussion that follows reference is made only to the maximum load.

For all the specimens tested in fatigue there was a rapid decrease in the maximum load within about 500 cycles; thereafter there was a gradual decrease in the maximum load until failure was imminent. At the higher stress levels, this drop in maximum load ranged from 200 to 300 lbs. for the 0.70 w/c mix specimens and from 500 to 1000 lbs. for the 0.45 w/c mix specimens. At the lower stress levels, this drop in maximum load was barely perceptible. In the case of the 0.45 w/c mix specimens, it was noticed that the audible cracking which occurred prior to failure resulted in abrupt drops in the maximum load.

The saturated specimens from both mixes that endured over a million cycles were lukewarm when removed from the fatigue machine. The air-dried specimens from the 0.70 w/c mix which were tested at the higher stress levels were warm at the time of failure, while the air-dried specimens from the 0.45 w/c mix were very hot at the time of failure. In fact, they were hot enough to cause the broken specimen to steam for a few seconds upon removal of the polyethylene film wrapping.

The observations just described are not necessarily indicative of the behavior of all the specimens. Relatively few specimens were observed in any great detail since it was impossible to monitor the tests 24 hours a day. However, it is felt that these observations, few as they might be, give information that cannot be disregarded.

Analysis

The fatigue test results for both cement paste mixes are tabulated in Tables 12 and 13, Appendix A. After completion of the fatigue testing for a particular grouping, the actual fatigue loadings were recomputed as stress levels using the average ultimate static strengths tabulated on page 35.

Figures 5 and 6 show the results of plotting these stress levels with their corresponding number of stress cycles. The commonly used semi-log coordinate system was chosen for presenting the S-N diagrams and to better illustrate the differences in the fatigue characteristics of the two pastes, a linear regression analysis was performed for each of the groupings.

The fitting of a straight line to the data of each grouping was

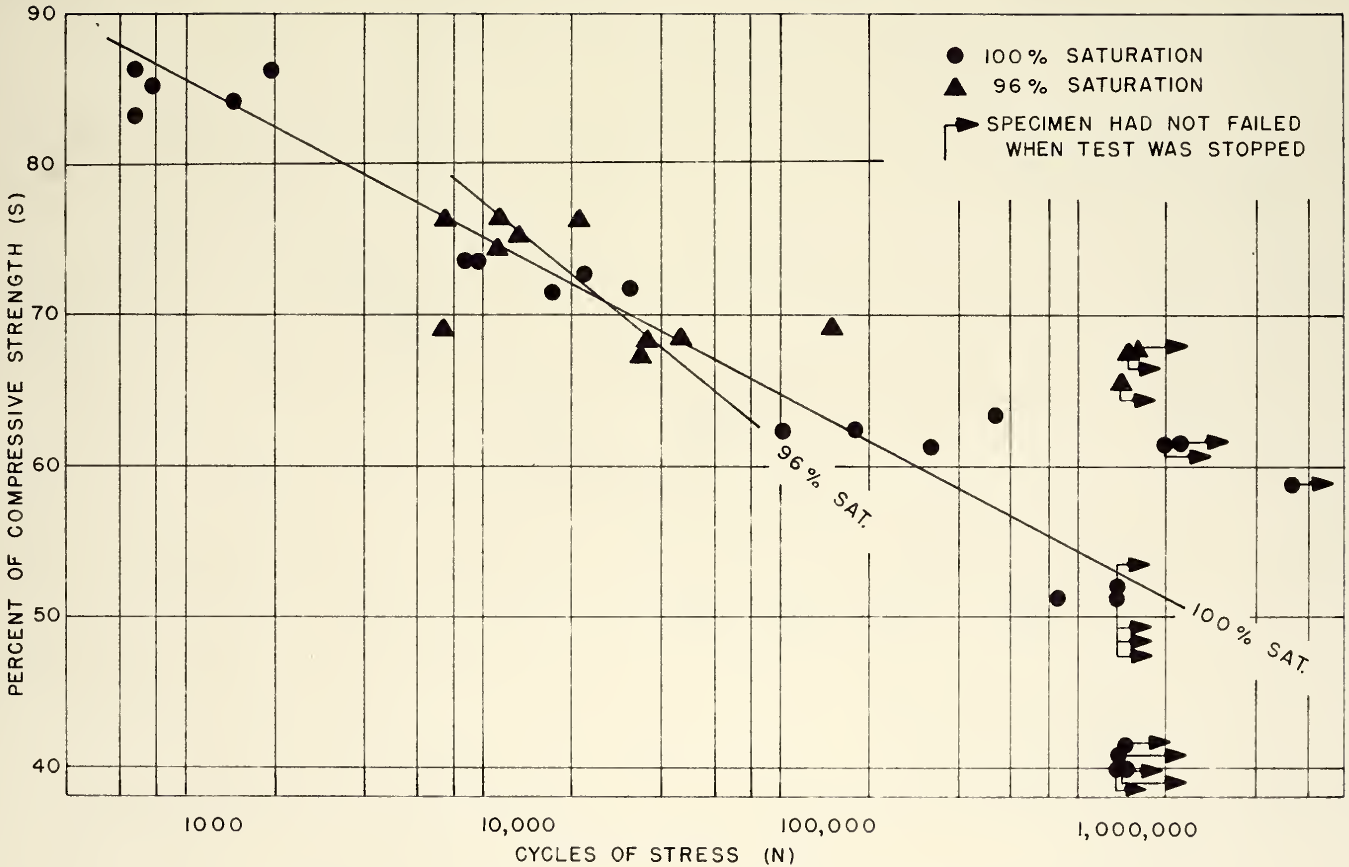

FIGURE 5. S-N DIAGRAM FOR 0.70 w/c CEMENT PASTE

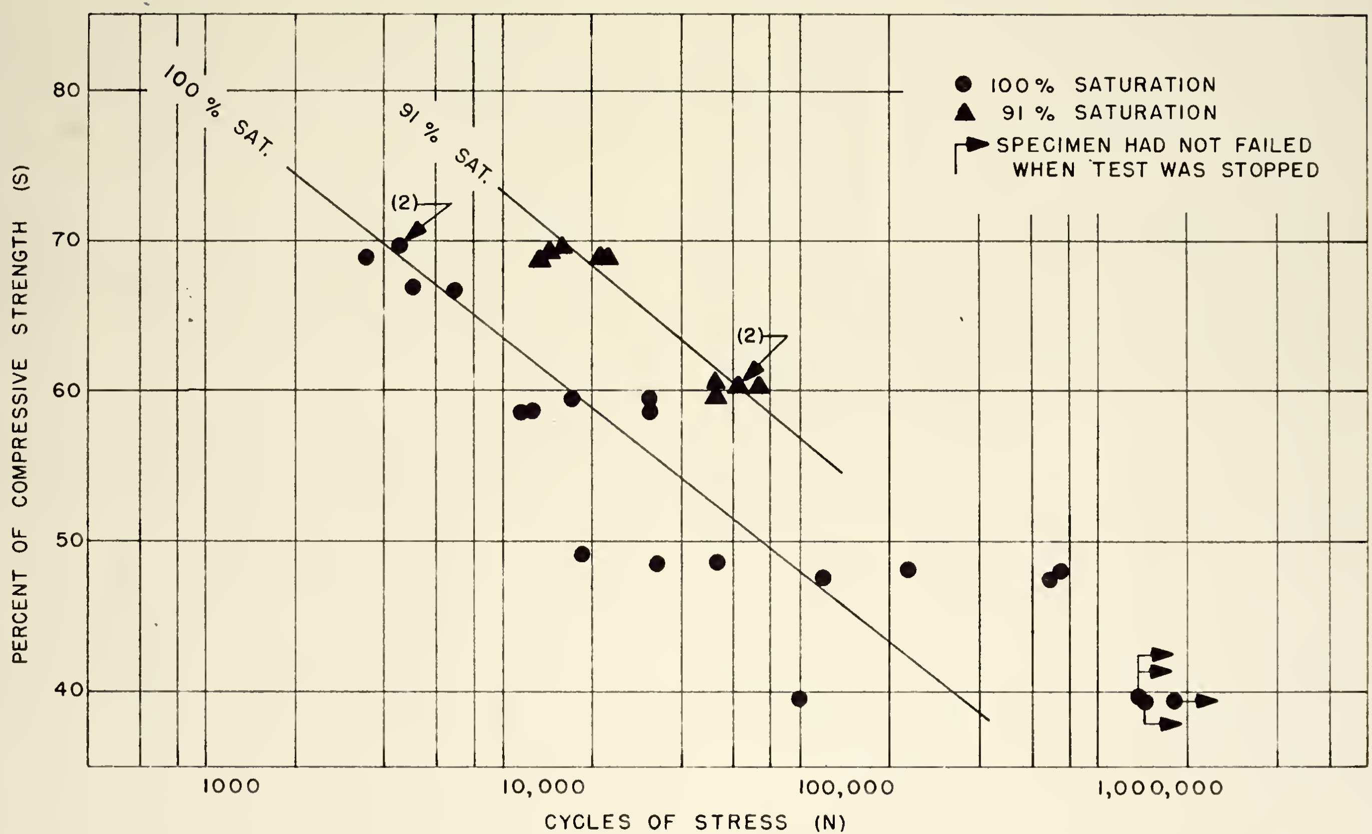

FIGURE 6. S-N DIAGRAM FOR 0.45 w/c CEMENT PASTE

accomplished by the method of least squares on the assumption that the S-N relationship within the range of stress levels studied is linear and that the transformed cycles to failure ($\text{Log}_{10}N$) are normally distributed. A sample calculation for this analysis is contained in Table 26, Appendix C.

The regression lines shown do not include the effect of those specimens which had not failed when the fatigue test was stopped. The equations of these lines are not shown because the curves should not be used to predict the fatigue performance of cement paste. Prediction curves would require considerably more data than was obtained. There is, however, sufficient data to justify the use of these lines to show the fatigue behavior of cement paste when it is subjected to changes in its water-cement ratio and its moisture content.

Results

The curves of Figures 5 and 6 have been reproduced in Figure 7 to better illustrate the fatigue behavior of the cement pastes. The data indicates that within the range of stress levels investigated, the number of cycles to failure for any value of percent compressive strength is considerably higher for a saturated cement paste with an open capillary structure than for a saturated cement paste with a dense structure. A similar comparison can be made between the 0.45 water-cement ratio paste at 91 percent of saturation and at 100 percent of saturation, whereas little difference in this regard is seen between the 0.70 water-cement ratio paste at 96 percent and 100 percent of saturation.

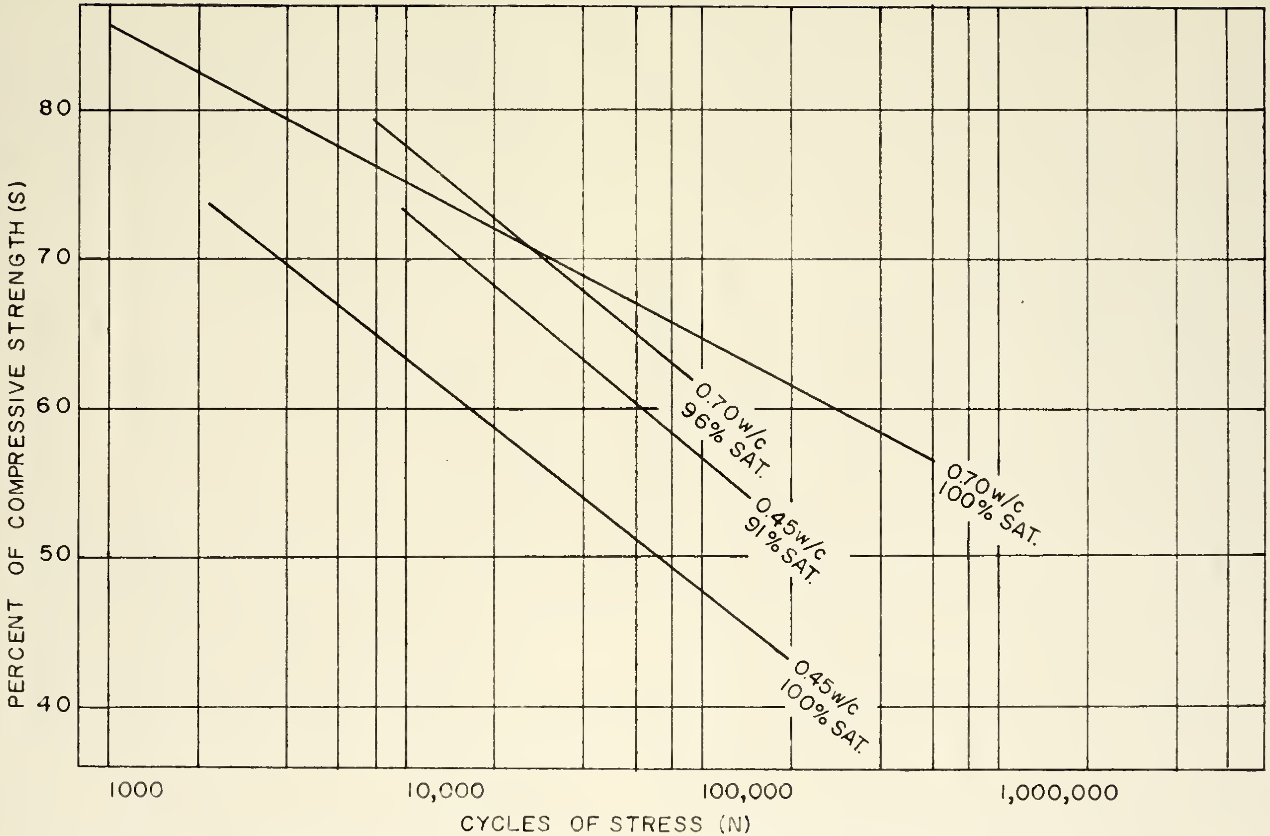

FIGURE 7. GRAPHICAL REPRESENTATION OF CEMENT PASTE FATIGUE DATA

These comparisons of fatigue characteristics of cement pastes loaded at equivalent percentages of their compressive strength suggest possible explanations of the fatigue mechanism that will be discussed later. It should be pointed out however that if one considers the absolute magnitude of the load, the number of cycles to failure at a particular loading is very much higher for the 0.45 water-cement ratio paste than for the 0.70 water-cement ratio paste.

Although not much information was obtained, the observed continual decrease in maximum load during a fatigue test suggests that the paste structure undergoes continuous physical changes, and that major cracking does not produce instantaneous failure.

Discussion of Results

Static Results

If the results of the static compression tests are considered in light of what is known or proposed concerning the behavior of cement paste, one finds that the results of this first part of the investigation are in agreement with existing knowledge and theory.

Hardened cement paste is known to be composed of cement gel and capillary pores, the capillary pores decreasing in quantity as the water-cement ratio of the paste is decreased. The cement gel consists of two components commonly called gel particles and gel pores, the volume of gel pores being a function of the degree of hydration of the cement particles.

The presence of capillary pores reduces the load carrying area per unit of gross area; thus a cement paste with an open capillary structure will be weaker than an equivalent section of cement paste with a dense structure. This is born out in this investigation, the 0.45 water-cement ratio paste specimens being approximately three times as strong as the 0.70 water-cement ratio specimens.

The effect of reducing the moisture content on the strengths of the pastes is not difficult to explain. The change in strength can be explained by the presence of shrinkage stresses in the cement paste. Both Czernin (18) and Powers (19) have offered theories to explain the process of shrinkage and since this writer prefers Powers' explanation, it will serve as a basis for the discussion that follows. Powers explains the shrinkage process as one which essentially occurs in the gel, the amount of shrinkage depending on the amount of water withdrawn from the gel. He says that those water molecules in direct contact with solid surfaces have the greatest effect and when this water is withdrawn, shrinkage will occur because the van der Waal forces start to draw the gel particles together as the forces producing displacement of gel particles are diminished. What happens, therefore, is that shrinkage from loss of water depends on how much of the loss is capillary water and how much is adsorbed water. When drying starts, most of the water loss is from the capillary pores and as the drying progresses, the water loss becomes predominantly adsorbed water. Both Powers and Czernin cite experimental data that illustrate the relationship between water loss and amount of shrinkage. A paste with few capillary pores (low water-cement ratio) will undergo shrinkage which is directly proportional to water loss. On the other hand, a paste with a considerable quantity of capillary pores (high water-cement ratio) will undergo very little shrinkage while loosing water, however, as the drying continues a point is reached when the shrinkage becomes directly proportional to the water loss.

Although no shrinkage was measured this relationship of water loss to theoretical amount of shrinkage and hence the development of shrinkage forces, is clearly evident in this investigation. Both the 0.70 and 0.45 water-cement ratio paste specimens lost about the same amount of water during their drying periods and, if Powers' theory is correct, then the strength of the air-dried 0.45 w/c paste specimens should be greater than the strength of the saturated paste specimens. This increase in strength will come from the presence of shrinkage stresses which develop as the water is withdrawn. These stresses are tensile, thus an additional compressive load must be applied to overcome them. The small, if any, gain in strength of the air-dried 0.70 w/c paste specimens is due to the lack of shrinkage stresses since the water loss was capillary water. That this water loss was capillary water can also be explained by what is known about the action of water in capillary tubes, that is, water in a large diameter capillary tube will evaporate much faster at a given relative humidity than water in a small diameter capillary tube. In this investigation, equivalent amounts of water were lost in considerably different time periods, the 0.70 w/c paste specimens loosing their water in 4 1/2 hours and the 0.45 w/c paste specimens loosing their water in 3 days. The only conclusion possible here is that the 0.70 w/c paste specimens definitely had a much more extensive capillary pore system.

Summarizing, we find that the physical make-up of the two pastes can explain the difference in strengths for the saturated condition, and the degree to which shrinkage stresses are present explains the change in strength when the pastes are air-dried.

Fatigue Results

It can be seen from Figure 7 that the S-N curve for the saturated 0.70 w/c paste is above that for the saturated 0.45 w/c paste. That is, at equivalent percentages of compressive strength, the 0.70 w/c paste withstands considerably more cycles of stress prior to failure than does the 0.45 w/c paste. A possible mechanism explaining this behavior is as follows: The 0.70 w/c paste is less brittle than the 0.45 w/c paste, the degree of brittleness being reflected in the manner in which the material fails in compression (20). It is capable of readjusting its structure and thus stress concentrations are slower to build up. Accordingly, crack initiation is delayed, crack propagation is not as rapid as in the 0.45 w/c paste, and the material is capable of withstanding more cycles to failure than its more brittle counterpart. It should be noted that the paste structure is the critical element because the load carrying gel particles are basically the same in both pastes.

Figure 7 also shows that the S-N curve for the air-dried 0.70 w/c paste is essentially superimposed on the curve for the saturated 0.70 w/c paste, but the curve for the air-dried 0.45 w/c paste lies above that for the saturated 0.45 w/c paste. These relative positions suggest that the change in fatigue properties of cement paste with air drying might be a result of the same factors that are considered to affect changes in static compressive strength. Reference to the tabulation on page 35 shows that the compressive strength of the air-dried and saturated 0.70 w/c pastes were approximately the same, but that the compressive strength of the air-dried 0.45 w/c paste was greater than that for the saturated 0.45 w/c paste. It is suggested that shrinkage stresses play a greater role in the fatigue strength than they do in the static strength because they serve to restrain crack propagation.

Crack propagation is an important factor in the fatigue failure of any material since final fracture is dependent of the extent of the crack pattern. Fatigue fracture is somewhat similar to brittle fracture in that the ability of the material to resist failure is dependent upon the random distribution of imperfections or weak spots. Brittle fracture occurs when the stress at one or more of these points reaches the strength of the material and little, if any, yielding precedes the failure (21). Although a material that fails in fatigue does so because of brittle fracture (even ductile steel shows a zone of brittle fracture), the process leading up to failure is different than that in the static situation. The difference is that the whole chain of events preceding fatigue fracture depends on a series of random processes. This is the reason for the pronounced scatter which is characteristic of all fatigue data. The important point is that fatigue failure starts at a few weak spots and if the propagation of the resulting cracks can be delayed, failure will be delayed. It is proposed that such a situation exists in the air-dried 0.45 w/c paste, that is, the shrinkage stresses in the vicinity of a newly formed crack are of sufficient magnitude to stop the propagation of the crack, at least temporarily. Once the section is weakened by an accumulation of these tiny cracks, the crack propagation proceeds as it does in the saturated 0.45 w/c paste.

Consideration was also given to alternate reasons for the observed pattern of fatigue behavior. At first glance the data suggest that the generation of hydraulic pressure in the pore water might account for the observed differences. However, the change in fatigue behavior brought about in the 0.45 w/c paste by a small amount of drying seems to eliminate this as a primary consideration.

Mechanism Proposed

Based on the preceding discussion, the following hypothesis is proposed for the mechanism of fatigue in cement paste:

> Fatigue failure in cement paste occurs because small cracks form and propagate under repeated applications of loads less than the static failure load. The resulting crack pattern weakens the section to the point where it cannot maintain the applied load. The development of this damaging crack pattern depends primarily (if not entirely) on the water-cement ratio of the cement paste and the presence of shrinkage stresses in the cement paste.
>
> The crack pattern is slower to develop in an open capillary structure cement paste than in a dense structure cement paste because the high water-cement ratio paste is less brittle and it can readjust its structure, thus delaying the buildup of stress concentrations.
>
> In addition, the crack pattern is slower to develop in a cement paste which has undergone a loss of gel water because

the shrinkage stresses that develop effectively restrain crack propagation and materially delay fatigue failure. However, the beneficial effect of the shrinkage stresses is reduced as shrinkage cracks are formed since they contribute to a reduction in the load carrying section.

FATIGUE OF PASTE-AGGREGATE COMBINATIONS

The objective of this part of the investigation was to determine if the introduction of aggregates into the cement paste would alter the fatigue situation. The procedures that were developed for manufacturing and testing the cement paste specimens were applied in this part of the investigation whenever possible. This investigation of paste-aggregate combinations consisted of two parts, one to determine the effect of adding aggregate to the paste and the other to determine the effect of aggregate type. The first was accomplished by diluting cement paste with natural aggregates and the second by diluting the cement paste with synthetic aggregates.

Design of the Experiment

As in the cement paste investigation, specimens were made one at a time and in an identical manner. The control on specimen strengths was similar to that obtained with the cement paste specimens and therefore it was decided to continue the practice of testing in fatigue at least five specimens at any given stress level.

Stress levels were chosen that resulted in short lives for the specimens tested in fatigue, thus making it possible to schedule a number of fatigue tests on any one day.

Upwards to twelve specimens were made each day, allowed to cure for 28 days, and then were tested statically or in fatigue. The testing format was the same as that used for the cement paste specimens, that is, saturated specimens were tested at the end of the curing period and air-dried specimens were tested right after completion of the air drying period.

Specimen size was 3 inches in diameter by 6 inches in height. This size was dictated by the maximum size of the aggregate and the load capacity of the fatigue testing machine.

To obtain concretes that could be compared with the cement pastes previously tested, it was necessary to use the same water-cement ratios for the paste portion of the concrete as were used in the cement paste investigation so that the dense and the open capillary paste structures that existed in the cement paste specimens would develop in the concrete specimens. The 0.45 water-cement ratio concrete was designed first, the ingredients being proportioned so that the resulting concrete was just workable enough to permit proper consolidation of the mix in the molds. These same volumes of paste and aggregate were then used for the 0.70 water-cement ratio concrete.

The concrete containing the natural aggregates was modified by the addition of entrained air since an earlier study (8) had indicated that the variability of fatigue data obtained from testing air-entrained concrete was less than that which would be obtained from testing non-air-entrained concrete. The concrete containing the synthetic aggregate was not modified by the addition of entrained air because it was felt that having an aggregate which was composed of only one material would significantly decrease the variability caused by having the natural aggregate which was composed of many materials.

Specimen Fabrication

Both the 0.70 water-cement ratio concretes and the 0.45 water-cement ratio concretes were manufactured in as nearly an identical manner as possible.

Materials

The cement and water were the same as used in the cement paste investigation.

The natural aggregate was composed of a crushed limestone coarse aggregate (material retained on the No. 4 sieve) and a natural sand fine aggregate (material passing the No. 4 sieve). The crushed limestone is a fine grained, low porosity material obtained in central Indiana. The source (laboratory designation 53-2S) is located in the St. Genevieve formation and is of Mississippian Age. The several sizes obtained from the quarry stockpiles were sieved in the laboratory to obtain a usable gradation of ½-inch maximum size. The resulting gradation and the physical properties of the coarse aggregate are shown in Table 2.

The natural sand is a local sand obtained from a river terrace deposit (laboratory designation 79-1G). This material meets the specification of the Indiana State Highway Commission for gradation 14 No. 2. The physical properties and gradation of this concrete sand are shown in Table 3.

The synthetic aggregate was manufactured in the laboratory by making cement paste of a desired strength, curing it for 28 days, crushing it, air drying it to constant weight, and finally sieving

TABLE 2

CHARACTERISTICS OF COARSE AGGREGATE 53-2S

Physical Properties

Dry rodded unit weight . . . . 94 lbs./cu. ft.

Bulk specific gravity 2.66

Absorption 0.72%

Gradation

Sieve size	Percent finer
1/2 inch	100
3/8 inch	55
No. 4	0

TABLE 3

CHARACTERISTICS OF FINE AGGREGATE 79-1G

Physical Properties

Bulk specific gravity 2.60

Absorption 1.28%

Gradation

Sieve size	Percent finer
No. 4	100
No. 8	90
No. 16	67
No. 30	42
No. 50	20
No. 100	6

Fineness modulus 2.75

it into various sizes and recombining the sizes into the desired gradation. Three different pastes were made, the water-cement ratios being 0.85, 0.52, and 0.36 by weight. A water reducing agent, WRDA, was used with the 0.36 w/c mix in order to make the mixture pourable. To permit visual separation of the aggregate from the cement paste of the concrete, a very strong organic dye called Congo Red was added to the mixing water of the aggregate. The quantity of dye used was very small, one gram per 2000 grams of cement.

Each of the three synthetic aggregates were similar in particle size and shape, and they had identical gradations. The main differences in the three aggregates were the strengths and the porosities. The physical properties and gradation of these three aggregates, which have been designated A-1, A-2, and A-3 as a means of identifying their respective water-cement ratios of 0.85, 0.52, and 0.36, are shown in Table 3. The values for bulk specific gravity and absorption listed in Table 3 were determined on the coarse aggregate fraction and the approximate ultimate compressive strength is based on the average of the strengths of representative 2-inch diameter by 4-inch high saturated specimens tested statically at the age of 28 days.

Darex, added at the mixer, was used as the air entraining agent for the air-entrained natural aggregate concrete.

Mix Design

Trial mixes established the maximum volume of aggregate that could be combined with the 0.45 water-cement ratio paste and still maintain sufficient workability to permit proper consolidation of

TABLE 4

CHARACTERISTICS OF SYNTHETIC AGGREGATES A-1, A-2, and A-3

Physical Properties

A-1 Aggregate (w/c = 0.85)

Dry rodded unit weight	55 lbs./cu. ft.
Bulk specific gravity	1.17
Absorption	43.7%
Approximate compressive strength	2900 psi.

A-2 Aggregate (w/c = 0.52)

Dry rodded unit weight	65 lbs./cu. ft.
Bulk specific gravity	1.48
Absorption	27.8%
Approximate compressive strength	8000 psi.

A-3 Aggregate (w/c = 0.36)

Dry rodded unit weight	76 lbs./cu. ft.
Bulk specific gravity	1.77
Absorption	18.6%
Approximate compressive strength	13,000 psi.

Gradation

Coarse Aggregate Fraction

Sieve size	Percent finer
1/2 inch	100
3/8 inch	55
No. 4	0

Fine Aggregate Fraction

Sieve size	Percent finer
No. 4	100
No. 8	90
No. 16	67
No. 30	42
No. 50	20
No. 100	6

Fineness modulus 2.75

the concrete mix in the mold. The trial mixes also served to establish the required amount of air entraining agent in the air-entrained mix.

The volume of aggregate was 68, 67, 66 and 67 percent of the total volume of concrete for the mixes made with the natural, A-1, A-2, and A-3 aggregates respectively. The volume of coarse aggregate was 31.3 percent of the total volume of concrete for each of the mixes.

The aggregate proportions in combination with the 0.70 water-cement ratio paste produced a high slump concrete mix, however, it was still possible to fill the molds without segregation occurring.

Mixing

The aggregate necessary for an individual specimen was saturated by adding water to it 24 hours prior to mixing. The excess water on the aggregate was determined immediately before mixing, and this amount was deducted from the calculated quantity of mixing water. When the air entraining agent was used, it was considered as part of the mixing water. Mixing was done in the Hobart electric mixer (Model N-50), but the previously used rounded bottom bowl and wire loop whip was replaced with a flat bottom bowl and a paddle and scraper arrangement. The total mixing time was 2 1/2 minutes for every mix; the first minute was at speed 1 for the aggregate and cement, the next 1/4 minute was for adding the water, and the final 1 1/4 minutes was at speed 2 for all the ingredients.

An air content determination was made on each air-entrained mix in one of two ways. The air contents of the 0.45 w/c concrete mixes were measured gravimetrically by using the known volume of the mold and the weight of fresh concrete in the mold. The air contents of the 0.70 w/c concrete mixes were measured volumetrically by means of a modified Chace air meter. The modification was one of enlarging the apparatus so that the volume of mortar used is approximately 60 cubic centimeters. The reason for using two different methods of measuring the air content was strictly one of convenience.

Casting

The molds used for the concrete mixes were made from split 3-inch inside diameter seamless steel tubing which was modified so that each mold could be bolted to a base plate. To eliminate any leakage of the mix water from the molds, the assembled molds were sealed with paraffin. The casting procedure for the 0.45 w/c concrete mixes consisted of filling the mold in three layers; each layer being subjected to 25 roddings with a 3/8-inch rounded rod, an up and down motion with a 1/4-inch wide trowel around the inside of the mold, and finally a tapping of the sides of the mold with a hard rubber mallet. All of this was then followed by a final troweling of the insides of the mold and a final tapping of the sides of the mold with the mallet. The casting procedure for the 0.70 w/c concrete mixes was simply one of filling the mold in three layes, each layer being rodded a few times with the 3/8-inch rod.

Curing

Immediately after casting, the molds were covered to reduce the loss of water by evaporation. The specimens were stored in the molds for 24 hours at room temperature and were then removed from the molds and stored for 27 days in a saturated lime solution at a temperature of 75°F.

Test Specimen Preparation

Prior to obtaining an age of 28 days, the 3-inch diameter by 6-inch high specimens were removed from the saturated lime solution for a period just long enough to permit the ends to be capped with a sulfur-carbon mixture (trade name - Vitrobond). The exception to this procedure was the long-time air-dried specimens and the oven-dried specimens which were capped after the drying period.

The saturated specimens scheduled for static tests and fatigue tests were handled exactly in the same manner as the cement paste specimens were handled, that is, the specimens were kept wet throughout the test.

Air-dried specimens were also handled as the cement paste specimens had been handled, that is, the static and fatigue tests took place upon completion of the drying period and the fatigue specimens were wrapped with polyethylene film.

The actual air drying was accomplished two ways. The first way was the same as that used for the cement paste specimens. The concrete specimens were placed in the special drying room for the specified period at the age of 28 days. The drying period for both the 0.70 and 0.45 w/c concrete specimens was 3 hours and the resulting water content was approximately 95 percent of that at saturation. The second way of air drying involved the storing of the specimens out in the open in the laboratory for five weeks. This drying period resulted in water contents that were 24 and 47 percent of that at saturation for the 0.70 and 0.45 w/c concretes respectively.

The oven-dried specimens were dried to constant weight at 220°F, the process taking 4 days.

Static Compression Tests

Procedure

Saturated specimens were tested at the age of 28 days for their unconfined ultimate compressive strength. The 3-hour air-dried specimens were tested right after the completion of the air drying period, while the 5-week air-dried specimens and the oven-dried specimens were tested two days after the completion of the drying period. All the static compression tests were performed in the previously mentioned Riehle testing machine.

Analysis

The static strength data for both the 0.70 and 0.45 water-cement ratio natural aggregate concretes are presented in Tables 14 and 16, Appendix B.

Average strengths and air contents along with their respective coefficients of variation for the different groupings are presented in Table 5. The only other analysis performed was an analysis of the effect of the air content of each specimen on its static compressive strength. This analysis indicated that the strengths of the 0.70 w/c concrete specimens were unaffected by variations in air content, and

TABLE 5

PHYSICAL PROPERTIES OF THE NATURAL AGGREGATE CONCRETES

w/c	Degree of Saturation (%)	Number of Specimens	Average Compressive Strength (psi)	Coefficient of Variation (%)	Average Air Content (see footnote) (%)	Coefficient of Variation (%)
0.70	100	9	2875	3.1	11.0	8.5
	95	9	2931	4.5	10.6	5.9
	24	9	2900	4.1	11.3	6.6
	0	11	2754	7.5	10.3	6.1
0.45	100	13	4437	7.8	9.3	8.7
	95	12	4383	8.8	9.0	12.1
	47	11	6113	7.3	7.2	11.1
	0	8	4550	11.9	8.4	11.8

The average air content of 76 specimens from the 0.70 w/c mix design is 10.8 percent and the coefficient of variation is 7.6 percent.

The average air content of 78 specimens from the 0.45 w/c mix design is 8.4 percent and the coefficient of variation is 16.1 percent.

that the strengths of the 0.45 w/c concrete specimens were affected slightly by variation in the air content. This effect on the 0.45 w/c concrete specimens was not considered to be great enough to warrant adjustment of the fatigue stress levels.

The static strength data for both the 0.70 and 0.45 water-cement ratio synthetic aggregate concretes are presented in Tables 18 and 19, Appendix B.

Average strengths and their respective coefficients of variation for the various groupings are presented in Table 6. Also included in this table are pertinent aggregate strengths, paste strengths, and modes of failure.

Results

Those characteristics of the natural aggregate concretes and the synthetic aggregate concretes which formed the basis for the analysis of the fatigue data have been summarized in Tables 5 and 6. Although it was impossible to keep a continuous check on the suitability of each specimen as was done with the cement paste specimens by testing the accompanying middle specimen, the data for both types of concrete indicate that the procedure adopted for making the specimens kept the strengths under reasonably good control. The control over the air contents was not as good, however, this may be partially due to the difficulty in obtaining precise measurements.

Fatigue Tests

The fatigue tests in this part of the investigation were conducted at two stress levels for the natural aggregate concretes and one stress

TABLE 6

PHYSICAL PROPERTIES OF THE SYNTHETIC AGGREGATE CONCRETES

w/c	Degree of Saturation (%)	Number of Specimens	Average Compressive Strength (psi)	Coefficient of Variation (%)	Aggregate Designation	Approx. Aggregate Strength (psi)	Approx. Cement Paste Strength (psi)	Failure Type[1]
0.70	100	5	1944	2.1	A-1	2900	3200	Bond[2]
	100	7	2853	3.8	A-2	8000	3200	Bond
0.45	100	5	3614	2.6	A-1	2900	9600	Bond & Aggregate[3]
	100	7	4993	3.0	A-2	8000	9600	Mostly Aggregate
	100	8	6014	5.2	A-3	13000	9600	Mostly Aggregate

1. Deduced from the appearance of the fractured specimens.

2. The bond failure referred to is at the coarse aggregate interface.

3. The aggregate failure referred to is failure through the aggregate.

level for the synthetic aggregate concretes. The two stress levels were considered sufficient to establish the effect of the variables being investigated since good control was obtained on the strengths of the particular concretes.

Procedure

All the fatigue tests in this part of the investigation were conducted in the Krouse-Purdue Fatigue Testing Machine. The various procedures necessitated by the operating characteristics of the machine and the objective of the investigation, which were discussed with respect to the fatigue testing of the cement paste specimens, are also applicable to the testing of the concrete specimens.

Specimen Behavior

There was no discernible difference in the type of fracture that occurred for the statically tested specimens and the fatigue tested specimens. The type of failure for all the concretes tested was the "cone" type of failure or slight variations of it.

In the case of the natural aggregate concretes, both concretes experienced failure around the coarse aggregate pieces, but the appearance of the exposed surfaces differed in that there was a mortar layer on the aggregate surface for the 0.70 w/c concrete and a relatively clean aggregate surface for the 0.45 w/c concrete. There was some failure through the aggregate for the 0.45 w/c concrete, but failure around the aggregate predominated.

In the case of the synthetic aggregate concretes, the failure was around the aggregate, for the two 0.70 water-cement ratio concretes, about equally divided between around the aggregate and through the aggregate for the 0.45 w/c concrete containing the weak aggregate, and almost entirely through the aggregate for the two 0.45 w/c concretes containing the medium strength and strong aggregates. These failures are shown in Figures 8, 9, 10, 11, and 12.

The concrete specimens behaved much the same way as the cement paste specimens when tested in the fatigue machine. A quick decrease in the maximum load was characteristic of all the concrete specimens and this decrease varied from a few hundred pounds to about a thousand pounds. After this initial decrease, there was little, if any, change in the maximum load until short of failure.

Specific information on the behavior of the specimens short of failure is incomplete, therefore, only those situations where detailed observations were made are mentioned.

The 0.45 w/c natural aggregate concrete which had been air dried to a water content of 47 percent of that at saturation underwent a gradual reduction in the maximum load a few thousand cycles before the final failure. In contrast, the other 0.45 w/c natural aggregate concretes did not give such an early warning of final failure.

This advance warning of final failure varied with the 0.45 w/c synthetic aggregate concretes; those containing the A-1 aggregate signaled failure some 2000 cycles ahead, those containing the A-2 aggregate signaled failure some 400 cycles ahead, and those containing the A-3 aggregate gave hardly any warning.

Analysis. The fatigue test results for the natural aggregate concretes are tabulated in Tables 20 and 21, Appendix B and those

FIGURE 8. TYPICAL FAILURE FOR 0.70 w/c A-1 AGGREGATE CONCRETE

FIGURE 9. TYPICAL FAILURE FOR 0.45 w/c A-1 AGGREGATE CONCRETE

FIGURE 10. TYPICAL FAILURE FOR 0.70 w/c A-2 AGGREGATE CONCRETE

FIGURE 10. TYPICAL FAILURE FOR 0.45 w/c A-2 AGGREGATE CONCRETE

FIGURE 12. TYPICAL FAILURE FOR 0.45 w/c A-3 AGGREGATE CONCRETE

for the synthetic aggregate concretes are tabulated in Tables 22 and 23, Appendix B.

The actual fatigue loadings were recomputed as stress levels using the average ultimate static strengths presented in Tables 5 and 6, and then these stress levels, along with their corresponding number of stress cycles, were plotted as shown in Figures 13, 14, and 15.

The method of least squares was used to fit curves to those groupings where sufficient data was available. This procedure was identical to that used for the cement paste fatigue data and the same limitations on the use of the least square lines that applied then, apply to this collection of data.

The oven-dried 0.70 w/c natural aggregate concrete was tested at only one stress level, therefore, the least squares method could not be applied to this data. A short line is shown on Figure 13 to help locate the position of the oven-dried data. This line was positioned by plotting the mean of the five stress level values and the mean of the logarithrms of the five stress cycles to failure values. No data is shown on Figure 14 for oven-dried 0.45 w/c natural aggregate concrete because the supply of specimens was depleted while trying to find a stress level that would permit the accumulation of a few thousand stress cycles. There was some indication that a stress level of about 65 percent would have worked.

Results

The curves of Figures 13 and 14, and the "mean" positions of the

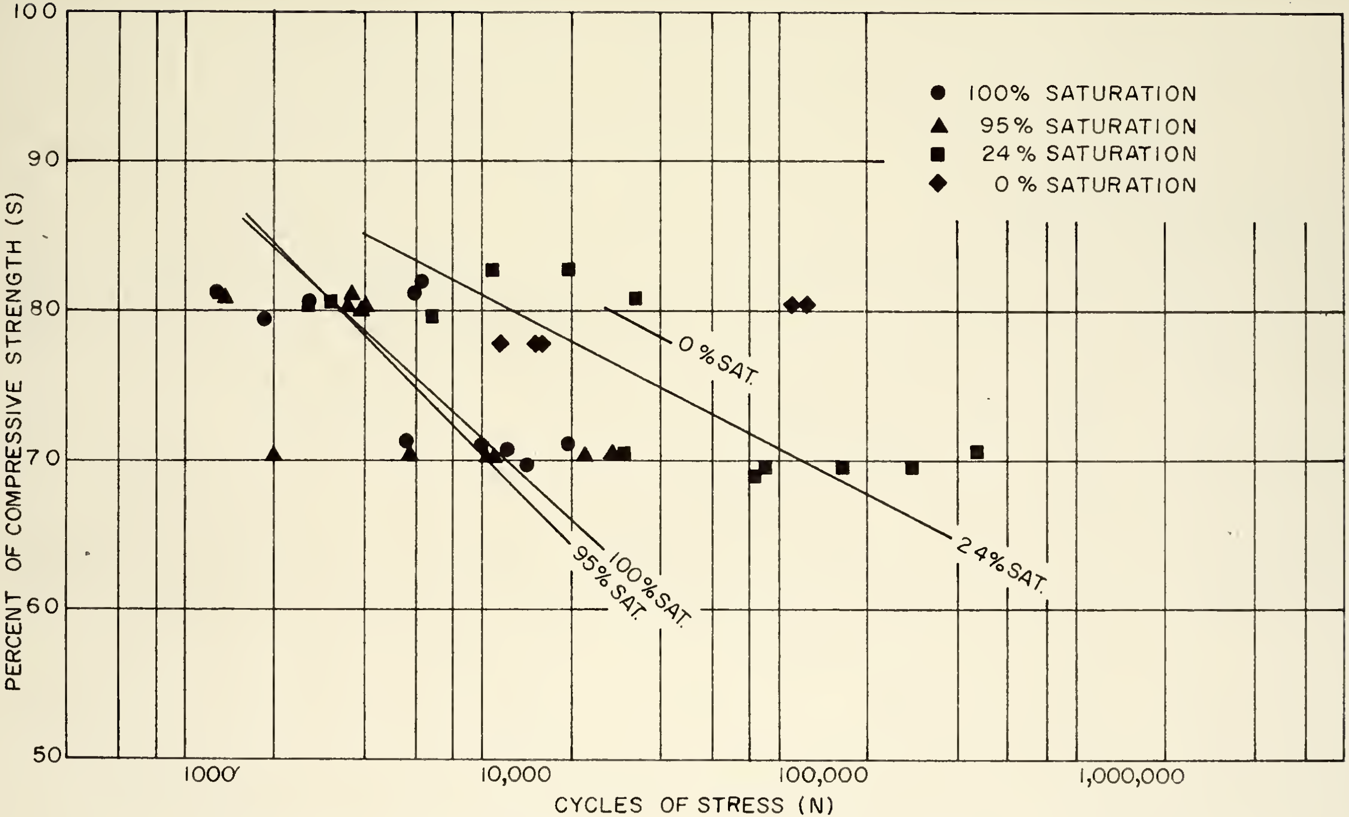

FIGURE 13. S-N DIAGRAM FOR 0.70 w/c NATURAL AGGREGRATE CONCRETE

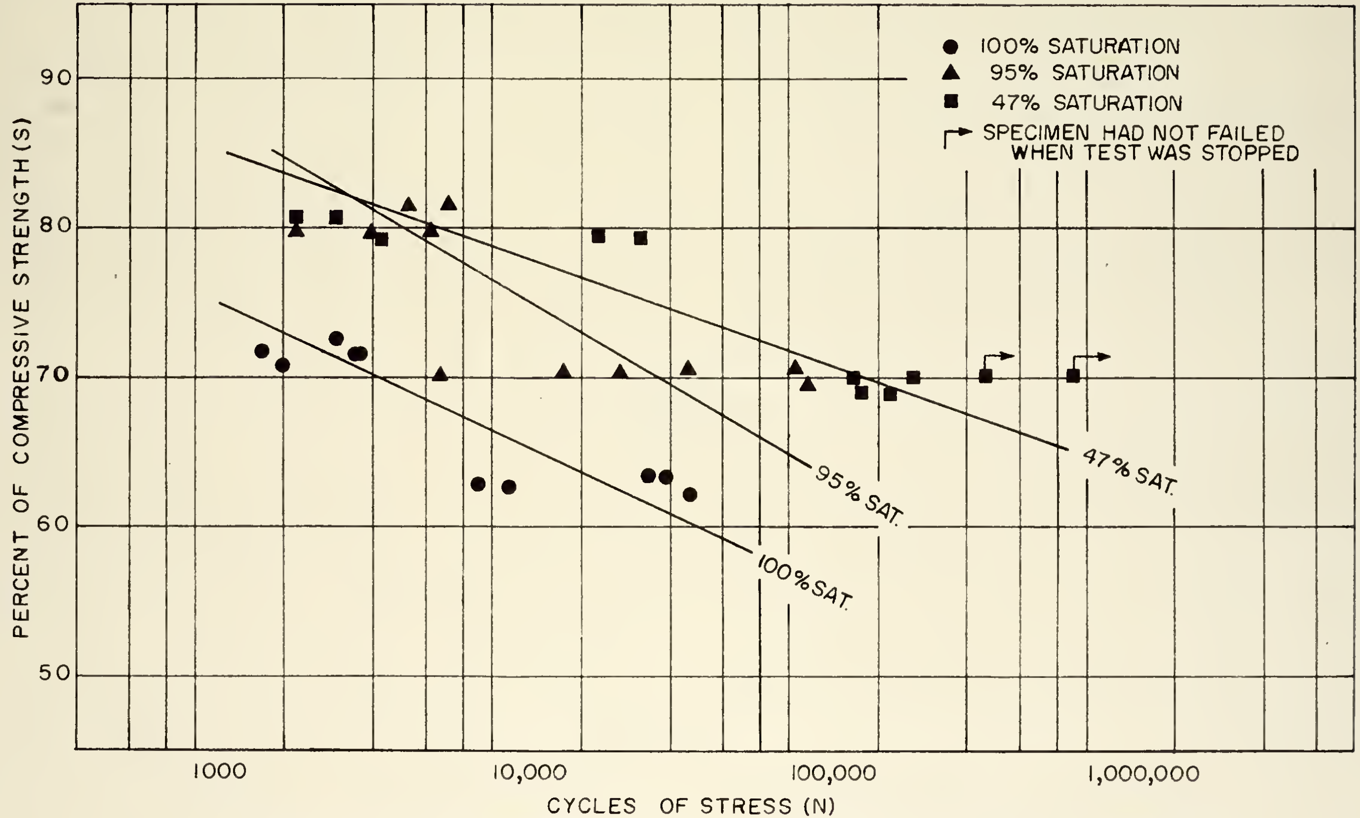

FIGURE 14. S-N DIAGRAM FOR 0.45 w/c NATURAL AGGREGATE CONCRETE

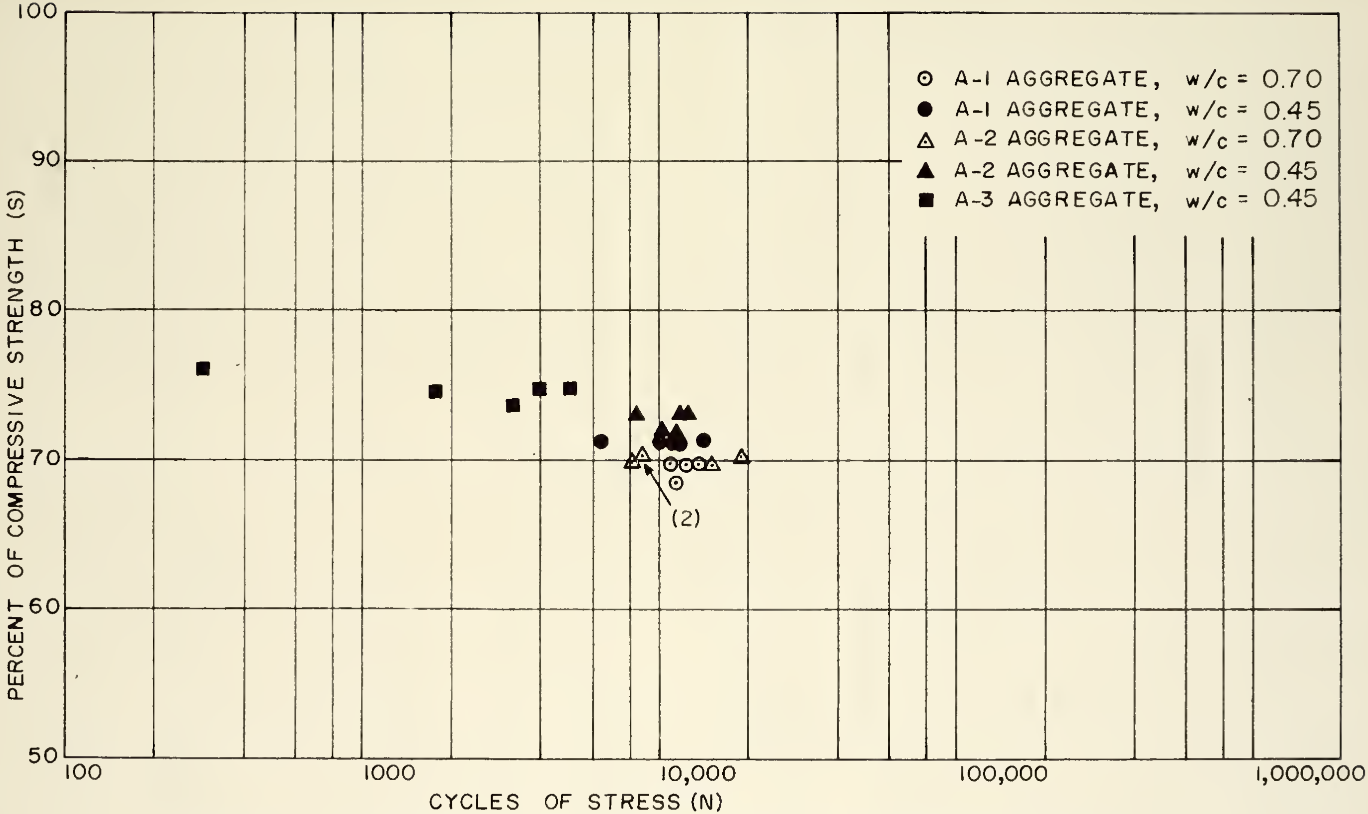

FIGURE 15. S-N DIAGRAM FOR THE SYNTHETIC AGGREGATE CONCRETES

data in Figure 15 have been reproduced in Figure 16 to better illustrate the fatigue behavior of the concretes. The data indicate that within the range of stress levels investigated, the number of cycles to failure for any value of percent compressive strength is higher for a saturated natural aggregate concrete with an open capillary structure cement paste than for a saturated natural aggregate concrete with a dense structure cement paste. A similar comparison can be made between the 0.45 water-cement ratio natural aggregate concrete at 95 percent of saturation and at 100 percent of saturation, and also at 47 and 95 percent of saturation. On the other hand, little difference in this regard is seen between the 0.70 water-cement ratio natural aggregate concrete at 95 and 100 percent of saturation, but the comparison can be made between the concrete at 24 and 95 percent of saturation, and also at zero and 24 percent of saturation. Tests of the 0.45 w/c natural aggregate concrete at zero percent of saturation were unsuccessful, but the indications were that instead of an increase in cycles to failure over that at 47 percent of saturation, there was a very large decrease.

The results of the testing of the saturated synthetic aggregate concrete are unlike those of the saturated natural aggregate concrete in that there is no discernible difference in fatigue behavior due to the water-cement ratio of the concrete. Figure 15 suggests that if all the synthetic aggregate concrete specimens had been tested at the same stress level, the number of cycles to failure would be essentially the same for all the concretes.

These comparisons of fatigue characteristics of concrete loaded

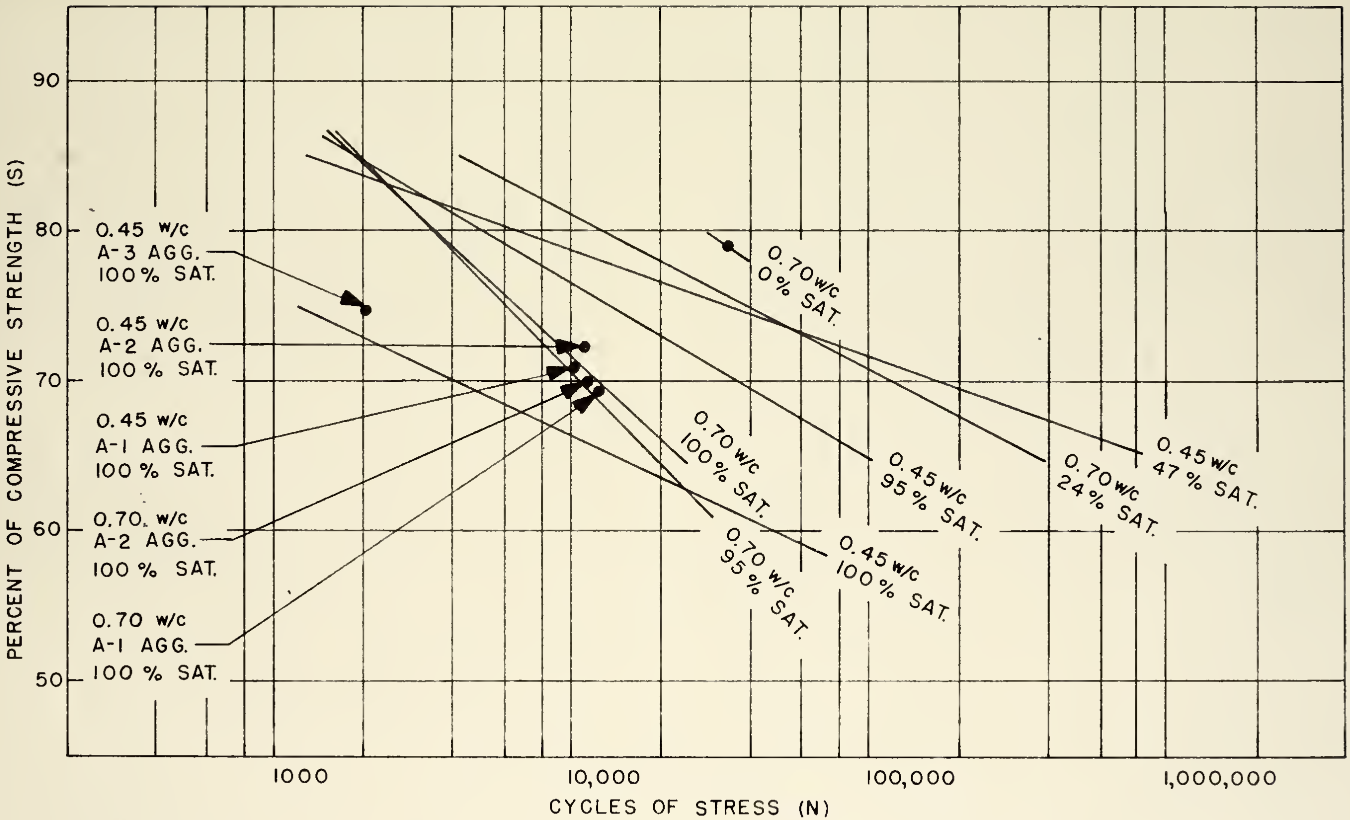

FIGURE 16. GRAPHICAL REPRESENTATION OF CONCRETE FATIGUE DATA

at equivalent percentages of their compressive strength suggest possible explanations of the fatigue mechanism that will be discussed later. It should be pointed out, however, that if one considers the absolute magnitude of the load, the number of cycles to failure at a particular loading is very much higher for the 0.45 water-cement ratio concrete than for the 0.70 water-cement ratio concrete.

Discussion of Results

Static Results

It is apparent from Table 7 that the strength of the aggregate has a pronounced effect on the strength of the concrete. However, it also appears that there is an interaction between the cement paste and the aggregate (or at least the synthetic aggregate) since the 0.45 w/c concrete containing the weak synthetic aggregate is stronger than the aggregate alone, while the 0.45 w/c concrete containing the strong aggregate is weaker than the cement paste alone.

The saturated natural aggregate concretes are complicated by the presence of entrained air, a strong coarse aggregate (about twice as strong as the stronger of the synthetic aggregates), and a fine aggregate that can be considered as strong. The presence of the entrained air in the two natural aggregate concretes accounts for some of the loss in strength from that of the cement paste by itself. The specific effect of the aggregates is difficult to pinpoint because apparently the effect varies. The strength of the saturated 0.70 w/c natural aggregate concrete is about 90 per cent of the strength of the saturated cement paste by itself and the strength of the saturated

TABLE 7

CEMENT PASTE AND CONCRETE STATIC STRENGTHS

w/c	Degree of Saturation (%)	Approximate Compressive Strength				
		Cement Paste (psi)	Natural Aggregate Air-Entrained Concrete[1] (psi)	A-1 Aggregate Concrete[2] (psi)	A-2 Aggregate Concrete[3] (psi)	A-3 Aggregate Concrete[4] (psi)
0.70	100	3200	2900	1900	2900	
	96	3500				
	95		2900			
	24		2900			
	0		2800			
0.45	100	9600	4400	3600	5000	6000
	95		4400			
	91	10900				
	47		6100			
	0		4600			

1. Approximate compressive strength of limestone aggregate is 26000 psi.
2. Approximate compressive strength of A-1 aggregate is 2900 psi.
3. Approximate compressive strength of A-2 aggregate is 8000 psi.
4. Approximate compressive strength of A-3 aggregate is 13000 psi.

0.45 w/c concrete is about 45 per cent of the strength of the saturated paste. A further difficulty in pinpointing this aggregate effect is that each of the two mix designs had the same type of aggregate, the same aggregate gradation, the same volume of cement paste, and essentially the same volume of entrained air. About the only major cause to consider is the concept of bond failure which has been the subject of a number of reçent investigations. Hsu et al. (22) have shown that cracks at the interface between coarse aggregate and mortar are widespread even in nonloaded concrete. They also found that as concrete is loaded, mortar cracks begin to increase, eventually connecting with the bond cracks to form continuous crack patterns. Apparently more is involved, because Alexander (23) showed that the cement-aggregate bond strength increases with decreasing water-cement ratio and application of this property to the situation at hand would lead one to believe that the 0.45 w/c concrete should be much closer to the strength of the cement paste alone than would the 0.70 w/c concrete if everything else were equal.

Further explanation of the effect of the aggregate on the static strength of the concrete is beyond the scope of this investigation. Important to the present study is that the aggregates used had a definite effect on the static strengths of the cement pastes.

The effect of reducing the moisture content on the strengths of the concretes is explained in terms of the shrinkage stresses present in the cement. The shrinkage of concrete is considerably less than that of cement paste due to the restraining influence of the aggregate, however, the paste in the concrete acquires the same shrinkage stresses as cement paste by itself when the moisture content reductions are equivalent.

Consider first the 0.70 w/c natural aggregate concrete. Reducing the moisture content to 95 per cent of that at saturation did not change the strength of the concrete because the water loss was almost entirely in the form of capillary water and thus no significant shrinkage forces were produced. The comparable cement pastes responded to the same moisture change in a like manner. Reducing the moisture content to 24 and zero per cent of that at saturation did not change the strength of the concrete because the gain in the paste strength due to shrinkage forces was offset by a decrease in paste strength due to shrinkage cracking. The shrinkage cracks result when the paste shrinks around the relatively incompressible coarse aggregate and the resulting tensile force exceeds the strength of the paste.

The 0.45 w/c natural aggregate concrete did not respond to the moisture changes in quite the same manner as did the 0.70 w/c concrete. Reducing the moisture content to 95 per cent of that at saturation did not increase the strength of the concrete as it did with the 0.45 w/c cement paste. One clue to this behavior is that the water loss for the concrete was accomplished in three hours, while it took three days for the cement paste to loose the same amount of water. The probable explanation is that the water loss was restricted to close to the surface of the concrete, thus allowing a quicker escape of the water. If the water loss was restricted to the surface of the specimen, then the shrinkage forces would have little, if any, effect on the compressive strength. That shrinkage forces existed is evidenced by the fatigue test results. Reducing the moisture content to 47 per cent of that at saturation produced a significant amount of shrinkage stresses and thus the reason for the increase in the strength of the concrete over that for the saturated condition. The oven-dried concrete shows little gain in strength over that of the saturated concrete because the shrinkage cracking offset the increase in strength of the paste due to the shrinkage forces.

Summarizing, we find that the addition of aggregate to cement paste influences the static strength of the paste by introducing new weak links. One such weak link can be the bond at the aggregate interface, another can be the strength of the aggregate, and yet another can be the restraining influence of the aggregate when the paste shrinks upon loss of gel water.

Fatigue Results

Figure 16 indicates that the natural aggregate concrete responded to changes in the water-cement ratio of its paste in a manner similar to that of the pure cement paste. That is, the S-N curve for the saturated 0.70 w/c concrete lies above the curve for the saturated 0.45 w/c concrete, this being the case for the 0.70 and 0.45 w/c pastes (Figure 7).

The natural aggregate concrete also responded to changes in moisture content in a manner similar to that of the pure cement paste. It can be seen from Figure 17 that a small reduction in moisture content from 100 percent of saturation did not materially change the

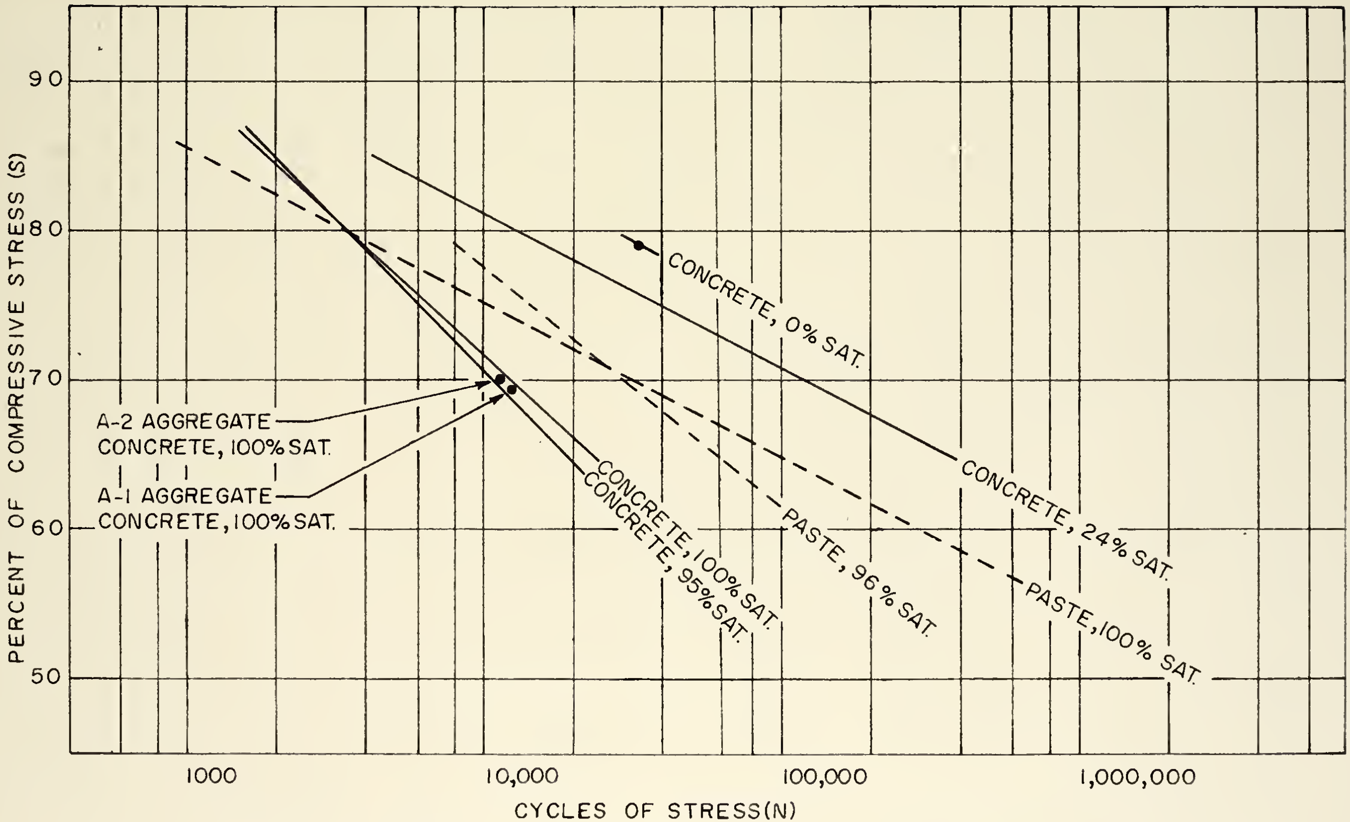

FIGURE 17. GRAPHICAL REPRESENTATION OF 0.70 w/c CEMENT PASTE AND CONCRETE FATIGUE DATA

position of the S-N curve for the 0.70 w/c concrete. This same behavior was characteristic of the 0.70 w/c paste. Figure 18 indicates that a small reduction in moisture content from 100 percent of saturation shifted the S-N curve for the 0.45 w/c concrete to a higher position just as a similar reduction in moisture content shifted the curve for 0.45 w/c paste upwards.

This behavior of the 0.70 and 0.45 w/c natural aggregate concretes suggests that the mechanism hypothesized for cement paste is operative in the concrete, that is, the fatigue behavior of the cement paste is a major factor in the fatigue behavior of concrete.

Further support for this mechanism is seen in the behavior of the natural aggregate concretes as their moisture contents were reduced below 90 percent of saturation. Figure 17 indicates that reducing the moisture content of the 0.70 w/c concrete from 95 percent of saturation to 24 percent of saturation shifted the S-N curve upward and that a further reduction in moisture content to zero percent of saturation resulted in an additional upwards shift of the S-N curve. Figure 18 indicates that reducing the moisture content of the 0.45 w/c concrete from 95 percent of saturation to 47 percent of saturation resulted in an upwards shift of the S-N curve. Reducing the moisture content of the 0.45 w/c concrete to zero percent of saturation did not result in an additional upwards shift of the S-N curve, but rather a pronounced downward shift of undetermined magnitude. This behavior of the two concretes is directly related to the shrinkage forces present in the cement paste. As more and more gel water is lost, the shrinkage forces increase and shrinkage cracks come

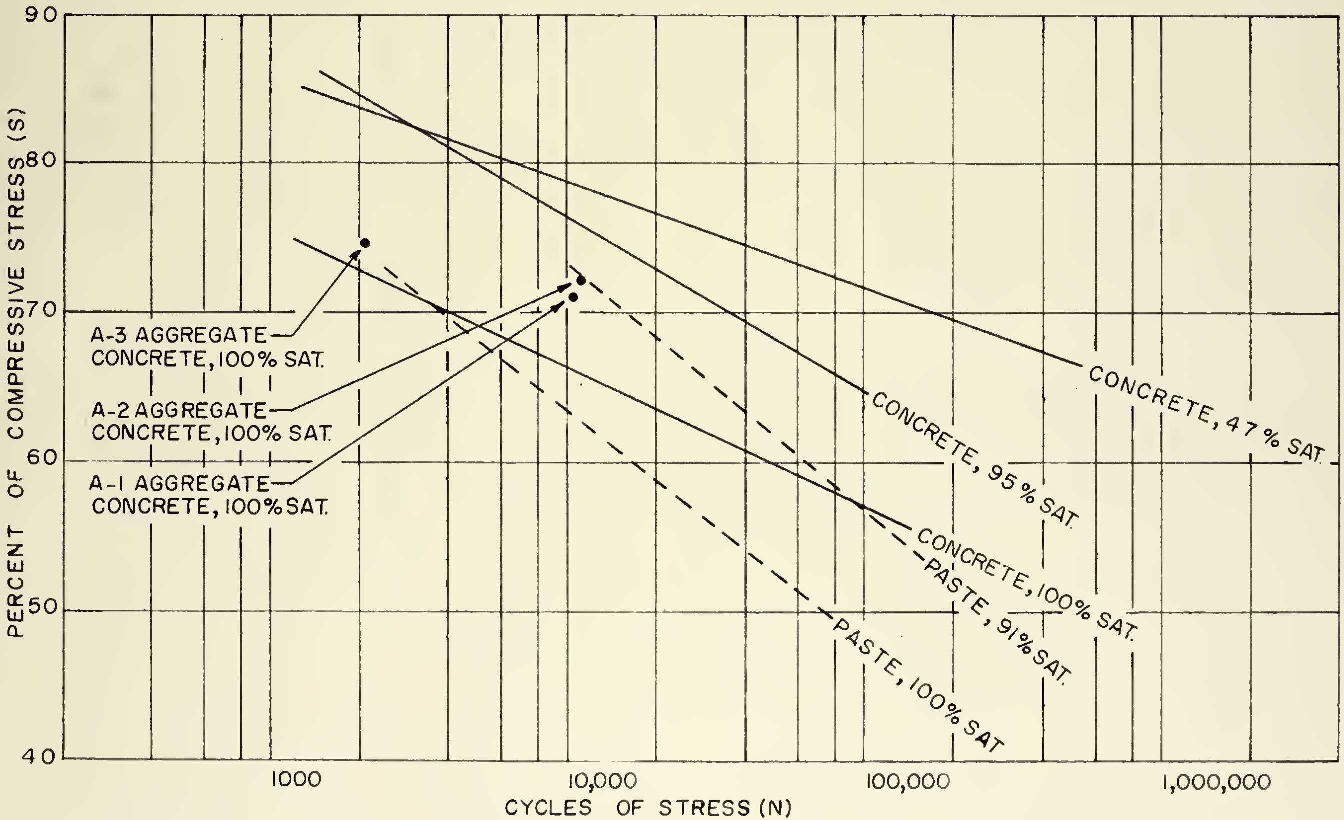

FIGURE 18. GRAPHICAL REPRESENTATION OF 0.45 w/c CEMENT PASTE AND CONCRETE FATIGUE DATA

into existence. The shrinkage cracks that develop are readily propagated by the fatigue action and hence the upwards shift of the S-N curve becomes less and less as the moisture content is continually reduced. In the case of the 0.45 w/c concrete at zero percent of saturation, the shrinkage cracks are very numerous and little propagation is needed to produce a section which cannot sustain the applied load.

Figures 17 and 18 also indicate that the aggregate, or at least its presence, has an influence on the fatigue behavior of the concrete. Figure 17 indicates that the S-N curves for the saturated and slightly dried 0.70 w/c concrete lie below the curves for the comparable 0.70 w/c pastes. The explanation proposed for this behavior is that the existing bond cracks in the concrete merely have to propagate, while the pure cement paste must first develop a crack system before propagation can proceed. Figure 18 indicates that the S-N curves for the saturated and slightly dried 0.45 w/c concrete lies above the S-N curves for the comparable 0.45 w/c pastes. It is suggested that this behavior, which is the opposite of that noted for the 0.70 w/c paste and concrete, is caused by the paste in the immediate vicinity of the aggregate having a less brittle structure than that of the main body of the paste in the concrete. In other words, the cracks are slower to initiate and thus the reason for the higher position of the S-N curves for the 0.45 w/c concrete. Once a crack pattern is established, crack propagation proceeds in the concrete as it does in the pure cement paste.

The fatigue behavior of the saturated synthetic aggregate concrete

(Figures 16, 17 and 18) does not appear to be consistent with the fatigue behavior pattern established by the saturated cement pastes and the saturated natural aggregate concretes. However, when consideration is given to the structure of the cement paste (aggregate and paste proper), the results obtained are compatible with those obtained for the pure cement pastes and the natural aggregate concretes.

The A-1 aggregate was made from a cement paste that had a water-cement ratio higher than 0.70, hence the aggregate paste is less brittle than the 0.70 w/c paste. As shown earlier, the less brittle paste endures a greater number of cycles to failure at a given percent of compressive strength than does the more brittle paste, thus the 0.70 w/c paste controls the fatigue behavior of the 0.70 w/c A-1 aggregate concrete and the A-1 aggregate controls the fatigue behavior of the 0.45 w/c concrete. Similarly the fatigue behavior of the A-2 aggregate concrete is controlled by the 0.70 w/c paste for the 0.70 w/c concrete and by the A-2 aggregate for the 0.45 w/c concrete. Unfortunately there are no data for a 0.70 w/c A-3 aggregate concrete, but as can be seen, the 0.45 w/c concrete is controlled by the 0.45 w/c paste.

The preceding analysis does not completely explain the fatigue results obtained for the synthetic aggregate concrete in that the fatigue performance of the five concretes tested is more alike than would be expected. It is suggested that the bond between the paste aggregate and the paste proper plays a major role in the establishment of the fatigue crack pattern, much more so than the bond existing in the natural aggregate concrete.

Mechanism Proposed

Based on the preceding discussion, the following hypothesis is proposed for the mechanism of fatigue in concrete:

> Fatigue failure in plain concrete occurs because small cracks form and propagate in the cement paste under repeated applications of loads less than the static failure load. The resulting crack pattern weakens the section to the point where it cannot maintain the applied load. The development of this damaging crack pattern depends primarily, if not entirely, on the water-cement ratio of the cement paste and the presence of shrinkage stresses in the cement paste.
>
> Concretes of different water-cement ratios develop a crack pattern in their cement paste in the same manner as does pure cement paste, that is, the crack pattern is slower to develop in the cement paste that has an open capillary structure than in the cement paste that has a dense structure and, in addition, the crack pattern is slower to develop in a cement paste that has undergone a loss of gel water.

SUMMARY AND CONCLUSIONS

The important findings of this investigation are that the fatigue behavior of cement paste is sensitive to changes in the water-cement ratio of the paste and to changes in the moisture content of the paste. It was also found that the fatigue characteristics of plain concrete are apparently governed primarily by the fatigue characteristics of the cement paste. The aggregate was found to have some influence on the fatigue behavior of the concrete and the explanation offered is that there are bond cracks present at the aggregate interface and that the paste surrounding the aggregate is not necessarily the same as the main body of the paste. In the case of the synthetic aggregate concrete, there was evidence that the concrete component that has the higher modulus of elasticity is the material in which the crack pattern develops. An unanswered question is whether the fatigue characteristics of a natural aggregate and a cement paste aggregate of equivalent modulus of elasticity are the same or are significantly different. If they are different, then the crack pattern might not develop in the concrete component with the higher modulus of elasticity as it did when both the aggregate and the paste were made from the same ingredients.

The findings of this investigation served as a basis for a hypothesis of the mechanism of fatigue in cement paste and for a hypothesis of the mechanism of fatigue in plain concrete. The mechanism proposed for cement paste is as follows:

> Fatigue failure in cement paste occurs because small cracks form and propagate under repeated applications of loads less than the static failure load and the resulting crack pattern weakens the section to the point where it cannot maintain the applied load. The development of this damaging crack pattern depends primarily, if not entirely, on the water-cement ratio of the cement paste and the presence of shrinkage stresses in the cement paste.

The mechanism proposed for plain concrete is as follows:

> Fatigue failure in plain concrete occurs because small cracks form and propagate in the cement paste under repeated applications of loads less than the static failure load and the resulting crack pattern weakens the section to the point where it cannot maintain the applied load. The development of this damaging crack pattern depends primarily, if not entirely, on the water-cement ratio of the cement paste and the presence of shrinkage stresses in the cement paste.

The proposed mechanism for plain concrete is different from the fatigue mechanism proposed by Murdock and Kesler (see page 17). They hypothesized that crack propagation is dependent upon the deterioration of the paste-fine aggregate bond whereas the present proposal hypothesizes that crack propagation is through the cement paste. The work reported in this thesis and the work conducted at the University of Illinois have indicated that the aggregate has a role in the fatigue characteristics of plain concrete but as yet, the extent of its role is unclear.

A previous study by this writer (8) indicated that entrained air does not affect the fatigue behavior of concrete, and the results of this study give no cause for disputing this conclusion. This earlier study is not directly comparable with the present study because of slightly different water-cement ratios and different proportions of paste and aggregate. The concretes, however, were over-dried, and when their S-N curves are compared with the curves of this study, one finds that their locations are in keeping with the findings of this study.

SUGGESTIONS FOR FURTHER WORK

The research reported in this thesis has considered the fatigue behavior of cement paste and plain concrete over a limited range of stress levels. The results of this testing suggest that a wider range of stress levels should be investigated to determine if there are any differences in the shapes of the S-N curves.

Also needed is an investigation of the effect of rewetting the concrete. If the proposed mechanism is correct, rewetted concrete, depending on the degree of saturation, should have a fatigue life less than that of dry concrete of the same composition. It is conceivable that if the rewetted concrete can be returned to the saturated condition, its fatigue life will be less than that for continuously saturated concrete because of the presence of shrinkage cracks caused by the initial drying.

Additional research that is of major interest and which might shed more light on the mechanism of fatigue in concrete are:

1. A comparison of the fracture surfaces of specimens that failed statically with those that failed in fatigue. This approach is suggested by the appearance of steel that has failed in fatigue. Steel shows two zones, one which is the fatigue zone (brittle failure) and the other which is the static zone (ductile failure). Even though concrete is not a ductile material like steel, if crack initiation and

propagation under fatigue conditions are different than those under static conditions, then there is a possibility that such a difference would show up under careful evaluation of photographs of fracture surfaces of concrete specimens tested in flexure.

2. Crack initiation in concretes could be studied by testing concretes made with aggregates which have been prepared so as to insure widely different bond strengths between the aggregate and the cement paste.

3. The effect of aggregate strength should be investigated further, particularly with natural aggregates whose strengths considerably below and above the strength of cement paste in the concrete.

4. Crack propagation could be studied in detail by comparing continuous recordings of the stress-strain relationship.

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APPENDIX A

TEST DATA FOR CEMENT PASTE MIXES

TABLE 8

DATA SUMMARY FOR 0.70 w/c CEMENT PASTE MIX DESIGN

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	4½ Hour Air-Dry Water Loss: Test Specimen (gm.)	4½ Hour Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
304	A	100	3800	N.T.[1]	N.A.[2]	N.A.	100
305			3740				
306			3730				
307			3720				
308			3740				
309			3870				
310			3770				
311			3800				
312			3730				
313			3390				
314			3610				
315			4010				
316			3970				
317			3840				
318			4090				
319			4180				
320			3540				
321			3480				
322			3670				
323			3850				
331			3410				
332			3200				
333			3320				
334			3310				
335			3420				
336			3300				
337	A	100	3240	N.T.	N.A.	N.A.	100

(continued)

TABLE 8 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	4½ Hour Air-Dry Water Loss: Test Specimen (gm.)	4½ Hour Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
338	A	100	3410	N.T.	N.A.	N.A.	100
340			3660	N.T.			
353			3810	3190			
354			T.F.[3]	3040			
355			T.F.	3190			
357			T.F.	3070			
359			T.F.	3260			
363			T.F.	3010			
367			3610	3350			
369	A		T.F.	2880			
374	B		T.F.	3150			
376			T.F.	3230			
378			3460	3190			
380			T.F.	3090			
385			T.F.	3030			
387			T.F.	3250			
390			3150	2700			
393			T.F.	3090			
395A			T.F.	3490			
395			T.F.	3310			
396			4170	3470			
397			T.F.	3430			
398			4100	3530			
399			4140	3700			
400			T.F.	3230			
401			3890	3490			
402			T.F.	3370			
403	B	100	T.F.	3250	N.A.	N.A.	100

(continued)

TABLE 8 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	$4\frac{1}{2}$ Hour Air-Dry Water Loss: Test Specimen (gm.)	$4\frac{1}{2}$ Hour Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
404	B	100	3360	3230	N.A.	N.A.	100
405			T.F.	3300			
406			T.F.	3400			
407			3830	3330			
408			T.F.	3440			
410			T.F.	3240			
411			T.F.	3270			
412			T.F.	3350			
413			T.F.	3270			
414			3510	N.T.			
415			T.F.	3100			
416	B		T.F.	3370			
564	C		3320	3400			
565			3410	3160			
572			3300	3270			
573			3210	3240			
580			3060	3010			
581			3110	3050			
582			T.F.	3350			
583			T.F.	3300			
592			T.F.	3190			
593			T.F.	3180			
597			T.F.	3180			
598			3280	3290			
614			3340	3070			
619			3230	3320			
620			3370	3290			
660	C	100	3240	3230	N.A.	N.A.	100

(continued)

TABLE 8 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	4½ Hour Air-Dry Water Loss: Test Specimen (gm.)	4½ Hour Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
664	C	100	3250	3460	N.A.	N.A.	100
668	↑	100	3150	3280	N.A.	N.A.	100
669	│	100	3200	3230	N.A.	N.A.	100
602	│	96	3300	3270	4.0	3.7	97
603	│	96	3530	3220	3.8	3.9	96
608	│	96	3670	3430	4.6	3.5	97
609	│	96	3630	3440	4.0	3.7	97
613	│	96	3420	3240	4.2	4.3	96
629	│	97 Est.[4]	T.F.	3210	3.2	2.8	97 Est.
630	│	97 Est.	T.F.	3360	3.4	2.2	98 Est.
633	│	97 Est.	T.F.	3490	3.0	3.1	97 Est.
634	│	97 Est.	T.F.	3260	3.2	3.1	97 Est.
637	│	98 Est.	T.F.	3270	1.8	1.3	99 Est.
638	│	98 Est.	T.F.	3340	1.6	2.0	98 Est.
643	│	96 Est.	T.F.	3330	4.0	3.4	97 Est.
644	│	96 Est.	T.F.	3350	4.0	3.5	97 Est.
647	│	97 Est.	T.F.	3470	3.2	3.0	97 Est.
648	│	97 Est.	3680	3430	3.0	3.1	97 Est.
655	│	95 Est.	T.F.	3330	4.8	4.7	95 Est.
656	│	96 Est.	T.F.	3000	4.4	4.1	96 Est.
659	↓	96 Est.	T.F.	3290	4.0	3.4	97 Est.
663	C	95 Est.	T.F.	3450	5.5	5.0	95 Est.

1. Specimen was not tested.
2. Not applicable.
3. Specimen was tested in fatigue.
4. This value is estimated. See Table 9 for calculations which establish this estimate.

TABLE 9

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 0.70 w/c CEMENT PASTE SPECIMENS

Cylinder Number	Air-Dry Water Loss		Additional Water Loss by Oven Drying		Total Water Loss	
	Test Specimen (gm.)	Middle Specimen (gm.)	Test Specimen (gm.)	Middle Specimen (gm.)	Test Specimen (gm.)	Middle Specimen (gm.)
602	4.0	3.7	101.2	97.4	105.2	101.1
603	3.8	3.9	100.8	95.9	104.6	99.8
606	4.6	3.5	99.4	96.1	104.0	99.6
609	4.0	3.7	101.2	95.2	105.2	98.9
613	4.2	4.3	99.5	95.0	103.7	99.3

Average total water loss for the five test specimens = 104.5 grams

$$\text{Estimated degree of saturation of test specimens} = \frac{104.5 - \text{Air-Dry Water Loss}}{104.5} \times 100$$

Average total water loss for the five middle specimens = 99.7 grams

$$\text{Estimated degree of saturation of middle specimens} = \frac{99.7 - \text{Air-Dry Water Loss}}{99.7} \times 100$$

TABLE 10

DATA SUMMARY FOR 0.45 w/c CEMENT PASTE MIX DESIGN

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength		3 Day Air-Dry Water Loss		Degree of Saturation of Middle Specimen (%)
			Test Specimen (psi)	Middle Specimen (psi)	Test Specimen (gm.)	Middle Specimen (gm.)	
364	B	100	9460	8320	N.A.[1]	N.A.	100
368			9310	6070			
370			8230	7590			
375			9390	8420			
377			9100	8190			
379			9540	9600			
381			9150	9500			
386			9400	9450			
391			9360	8230			
394			9050	5680			
396A	B		9520	9220			
422	C		9320	9480			
423			9610	9550			
425			9240	9700			
426			9260	B.S.[2]			
428			9490	9430			
429			9470	9610			
432			T.F.[3]	9800			
433			T.F.	9570			
437			T.F.	9720			
438			T.F.	9570			
442			10090	9820			
443	C	100	T.F.	9330	N.A.	N.A.	100

(continued)

TABLE 10 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength		3 Day Air-Dry Water Loss		Degree of Saturation of Middle Specimen (%)
			Test Specimen (psi)	Middle Specimen (psi)	Test Specimen (gm.)	Middle Specimen (gm.)	
448	C	100	T.F.	9910	N.A.	N.A.	100
449	↑	↑	B.S.	9520	↑	↑	↑
453			T.F.	10100			
454			T.F.	9940			
455			T.F.	10200			
456			T.F.	10100			
461			9790	B.S.			
462			T.F.	9960			
465			T.F.	10080			
466			9310	9070			
469			T.F.	9720			
470			9070	9810			
473			T.F.	9230			
474			B.S.	10010			
476			T.F.	9490			
479			T.F.	9640			
480			9290	9870			
481			T.F.	9910			
486			T.F.	9820			
487			9680	9720			
488			T.F.	9690			
493	↓	↓	T.F.	9870	↓	↓	↓
496	C	100	T.F.	9380	N.A.	N.A.	100

(continued)

TABLE 10 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	3 Day Air-Dry Water Loss: Test Specimen (gm.)	3 Day Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
498	C	100	T.F.	9350	N.A.	N.A.	100
538	↑	↑	B.S.	10030	↑	↑	↑
539			10120	10000			
540			10050	10010			
541			9880	9490			
542		↓	10040	9820	↓	↓	↓
543		100	10000	9670	N.A.	N.A.	100
489		93	10590	10830	6.1	5.3	93
494		97	10750	11040	2.5	3.0	96
495		96	10710	10930	3.0	3.6	97
497		94	10940	10840	5.3	4.2	95
502		95	10890	10830	4.3	3.4	96
503		95 Est.[4]	T.F.	10920	4.2	3.4	96 Est.
504		90 Est.	T.F.	11130	8.5	5.4	93 Est.
506		92 Est.	T.F.	10890	7.1	5.1	94 Est.
508		90 Est.	T.F.	11060	8.2	5.2	94 Est.
512		91 Est.	T.F.	11250	7.7	5.2	94 Est.
516		90 Est.	T.F.	11360	8.6	6.2	92 Est.
517		90 Est.	T.F.	11360	8.4	7.2	91 Est.
520		89 Est.	T.F.	11570	9.1	7.9	90 Est.
521		90 Est.	B.S.	11550	8.1	7.4	91 Est.
524		90 Est.	T.F.	11560	8.7	8.9	89 Est.
525		89 Est.	B.S.	10540	9.1	8.3	90 Est.
526		89 Est.	B.S.	10550	9.2	6.3	92 Est.
527	↓	90 Est.	T.F.	11340	8.3	8.0	90 Est.
531	C	89 Est.	11390	11680	9.2	9.0	89 Est.

(continued)

TABLE 10 (continued)

Cylinder Number	Made by Operator	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength: Test Specimen (psi)	28 Day Static Compressive Strength: Middle Specimen (psi)	3 Day Air-Dry Water Loss: Test Specimen (gm.)	3 Day Air-Dry Water Loss: Middle Specimen (gm.)	Degree of Saturation of Middle Specimen (%)
532	C	90 Est.	T.F.	10770	9.0	9.2	88 Est.
536	C	89 Est.	B.S.	11470	9.5	8.8	89 Est.
537	C	91 Est.	T.F.	B.S.	7.9	9.9	88 Est.
The specimens listed below were air-dried 6 days							
505	C	84 Est.	11450	9190	13.6	10.5	87 Est.
507	↕	87 Est.	11060	11070	10.8	8.5	89 Est.
513	↕	86 Est.	11500	11360	12.2	8.4	89 Est.
518	↕	86 Est.	B.S.	11500	11.7	7.4	91 Est.
519	C	88 Est.	10160	11490	10.4	8.2	90 Est.

1. Not applicable.
2. Bad specimen. Specimen either failed in a non-normal way at a very low load or specimen had visible faults (surface cavities or extreme surface cracking).
3. Specimen was tested in fatigue.
4. This value is estimated. See Table 11 for calculations which establish this estimate.

TABLE 11

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 0.45 w/c CEMENT PASTE SPECIMENS

Cylinder Number	Air-Dry Water Loss		Additional Water Loss by Oven Drying		Total Water Loss	
	Test Specimen (gm.)	Middle Specimen (gm.)	Test Specimen (gm.)	Middle Specimen (gm.)	Test Specimen (gm.)	Middle Specimen (gm.)
489	6.1	5.3	77.7	73.7	83.8	79.0
494	2.5	3.0	81.8	75.9	84.3	78.9
495	3.0	3.6	80.9	75.4	83.9	79.0
497	5.3	4.2	79.4	75.5	84.7	79.7
502	4.3	3.4	81.0	77.0	85.3	80.4
505	13.6	10.5	71.6	68.8	85.2	79.3
507	10.8	8.5	73.8	69.8	84.6	78.3
509	13.0	10.2	72.2	68.5	85.2	78.7

Average total water loss for the eight test specimens = 84.6 gm.

$$\text{Estimated degree of saturation of test specimens} = \frac{84.6 - \text{Air-Dry Water Loss}}{84.6} \times 100$$

Average total water loss for the eight middle specimens = 79.2 gm.

$$\text{Estimated degree of saturation of middle specimens} = \frac{79.2 - \text{Air-Dry Water Loss}}{79.2} \times 100$$

TABLE 12

FATIGUE TEST DATA FOR 0.70 w/c CEMENT PASTE MIX DESIGN

Cylinder Number	Degree of Saturation	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles	Static Strength After Fatigue Testing (lbs.)
354	100	4,600 (39.9)[1]	700 (6.1)[1]	1,400,000 →[2]	11,670 (39.4)[3]
355	↑		Test Malfunction[4]		
357			Test Malfunction		
359		4,600 (39.9)	300 (2.6)	1,456,000 →	10,420 (44.1)
363			Test Malfunction		
369		4,600 (39.9)	800 (6.9)	1,500,000 →	10,340 (44.5)
374		4,800 (41.6)	400 (3.5)	1,520,000 →	10,140 (47.3)
376		4,700 (40.7)	600 (5.2)	1,400,000 →	10,690 (44.1)
380		5,900 (51.2)	400 (3.5)	1,420,000 →	10,660 (55.4)
385		6,000 (52.0)	800 (6.9)	1,412,000 →	9,710 (61.8)
387		5,900 (51.2)	700 (6.1)	874,200	
393		5,900 (51.2)	400 (3.5)	1,420,000 →	10,310 (57.3)
395A		5,900 (51.2)	500 (4.3)	1,430,000 →	11,000 (53.7)
395		7,100 (61.6)	1000 (8.7)	2,040,000 →	11,440 (62.1)
397		7,100 (61.6)	300 (2.6)	2,320,000 →	13,110 (54.0)
400		7,200 (62.5)	900 (7.8)	180,300	
402		7,200 (62.5)	700 (6.1)	106,300	
403		7,300 (63.3)	700 (6.1)	545,600	
405	↓		Test Malfunction		
406	100	7,100 (61.6)	700 (6.1)	333,300	

(continued)

TABLE 12 (continued)

Cylinder Number	Degree of Saturation	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles	Static Strength After Fatigue Testing (lbs.)
408	100	6,800 (59.0)	800 (6.9)	5,400,000 →	11,660 (58.4)
410	↑	8,400 (72.9)	500 (4.3)	22,600	
411		8,500 (73.7)	600 (5.2)	8,900	
412		8,500 (73.7)	600 (5.2)	10,000	
413		8,200 (71.7)	800 (6.9)	17,600	
415		Test	Malfunction		
416		8,300 (72.0)	300 (2.6)	32,200	
582		8,500 (83.4)[5]	1000 (9.8)[5]	700	
583		8,600 (84.4)	900 (8.8)	1,500	
592		8,800 (86.4)	900 (8.8)	700	
593	↓	8,700 (85.4)	1000 (9.8)	800	
597	100	8,800 (86.4)	800 (7.9)	2,000	
629	97	8,500 (76.5)[6]	900 (8.1)[6]	11,600	
630	97	8,500 (76.5)	700 (6.3)	21,800	
633	97	8,400 (75.5)	900 (8.1)	13,400	
634	97	8,500 (76.5)	900 (8.1)	7,700	
637	98	8,300 (74.6)	900 (8.1)	11,600	

(continued)

TABLE 12 (continued)

Cylinder Number	Degree of Saturation	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles	Static Strength After Fatigue Testing (lbs.)
638	98	7,500 (67.4)	900 (8.1)	35,100	
643	96	7,600 (68.4)	800 (7.2)	47,000	
644	96	7,700 (69.3)	600 (5.4)	151,200	
647	97	7,500 (67.4)	600 (5.4)	1,555,000 →	11,590 (64.7)
655	95	7,600 (68.4)	500 (4.5)	36,100	
656	96	7,700 (69.3)	900 (8.1)	7,600	
659	96	7,300 (65.7)	800 (7.2)	1,433,000 →	10,870 (67.4)
663	95	7,500 (67.4)	1000 (9.0)	1,607,000 →	11,130 (67.4)

1. Figure in parentheses for cylinders 354 through 416 is the fatigue load expressed as a percentage of the average compressive strength of 40 saturated specimens (Y_{avg} = 3671 psi).

2. → indicates that specimen had not failed when test was stopped.

3. Figure in parentheses is the maximum fatigue load expressed as a percentage of the compressive strength of the specimen after its removal from the fatigue machine.

4. Test malfunction indicates data was discarded because of a machine failing or an operator error.

5. Figure in parentheses for cylinders 582 through 597 is the fatigue load expressed as a percentage of the average compressive strength of 14 saturated specimens (Y_{avg} = 3248 psi).

6. Figure in parentheses for cylinders 629 through 663 is the fatigue load expressed as a percentage of the average compressive strength of 6 air-dried specimens (Y_{avg} = 3538 psi).

TABLE 13

FATIGUE TEST DATA FOR 0.45 w/c CEMENT PASTE MIX DESIGN

Cylinder Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured	Static Strength After Fatigue Testing (lbs.)
432	100	20,100 (66.5)[1]	1000 (3.3)[1]	6,900	
433	↑	21,000 (69.5)	800 (2.6)	4,500	
437	│	20,800 (68.8)	1200 (4.0)	3,500	
438	│	21,000 (69.5)	800 (2.6)	4,500	
443	│	20,200 (66.8)	1200 (4.0)	4,900	
448	│	17,700 (58.5)	1200 (4.0)	11,500	
453	│	17,900 (59.2)	1000 (3.3)	17,100	
454	│	17,900 (59.2)	1100 (3.6)	31,100	
455	│	17,700 (58.5)	1200 (4.0)	12,500	
456	│	17,600 (58.2)	1100 (3.6)	31,300	
462	│	14,700 (48.6)	1000 (3.3)	53,400	
465	│	14,800 (49.0)	1000 (3.3)	18,600	
469	│	14,300 (47.3)	1000 (3.3)	704,300	
473	│	14,500 (48.0)	1200 (4.0)	754,200	
476	│	14,400 (47.6)	1000 (3.3)	120,100	
479	│	14,500 (48.0)	1400 (4.6)	231,400	
481	│	14,600 (48.3)	1100 (3.6)	33,000	
486	│	11,900 (39.4)	900 (3.0)	99,400	
488	│	11,800 (39.1)	800 (2.6)	1,802,000 →[2]	29,790 (39.6)[3]
493	│	11,800 (39.1)	1100 (3.6)	1,446,500 →	30,460 (38.7)
496	↓	11,900 (39.4)	1100 (3.6)	1,358,000 →	30,270 (39.4)
498	100	11,900 (39.4)	1000 (3.3)	1,375,000 →	28,410 (42.0)
503	95	23,600 (69.1)[4]	1500 (4.4)[4]	14,400	
504	90	23,700 (69.5)	1000 (2.9)	15,400	
506	92	23,400 (68.6)	1300 (3.8)	13,200	

(continued)

TABLE 13 (continued)

Cylinder Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured	Static Strength After Fatigue Testing (lbs.)
508	90	23,500 (68.9)	1400 (4.1)	21,400	
512	91	23,500 (68.9)	1100 (3.2)	22,400	
516	90	Test Malfunction			
517	90	Test Malfunction			
520	89	20,300 (59.5)	1200 (3.5)	52,600	
524[5]	90	20,700 (60.6)	1000 (2.9)	51,800	
527[5]	90	20,500 (60.1)	1000 (2.9)	62,600	
532[5]	90	20,500 (60.1)	1100 (3.2)	71,900	
537	91	20,500 (60.1)	1300 (3.8)	62,800	

1. Figure in parentheses for cylinders 432 through 498 is the fatigue load expressed as a percentage of the average compressive strength of 17 saturated specimens (Y_{avg} = 9630 psi).

2. ⟶ indicates that specimen had not failed when test was stopped.

3. Figure in parentheses is the maximum fatigue load expressed as a percentage of the compressive strength of the specimen after its removal from the fatigue machine.

4. Figure in parentheses for cylinders 503 through 537 is the fatigue load expressed as a percentage of the average compressive strength of 6 air-dried specimens (Y_{avg} = 10,878 psi).

5. Surface cracking appeared after air drying and prior to start of fatigue test.

APPENDIX B

TEST DATA FOR CONCRETE MIXES

TABLE 14

DATA SUMMARY FOR 0.70 w/c NATURAL AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
683	100	12.2	2780	0 hrs.	N.A.[1]
684	↑	11.0	3040	↑	↑
685	│	12.0	2830	│	│
687	│	11.1	2850	│	│
688	│	12.0	2870	│	│
689	│	10.2	2960	│	│
690	│	9.2	T.F.[2]	│	│
691	│	9.6	T.F.	│	│
692	│	10.6	T.F.	│	│
693	│	9.1	T.F.	│	│
694	│	10.4	T.F.	│	│
695	│	11.4	T.F.	│	│
696	│	10.6	T.F.	│	│
697	│	11.6	T.F.	│	│
709	│	10.0	T.F.	│	│
710	│	11.1	T.F.	│	│
711	│	10.6	2760	│	│
719	↓	9.7	2920	↓	↓
735	100	10.0	2870	0 hrs.	N.A.
698	94	10.6	2720	3 hrs.	5.5
699	97	11.3	2980	↑	3.5
700	97	10.7	3000	│	3.0
701	97	10.0	3160	│	3.0
702	97	10.0	3030	│	3.5
712	97	11.6	2800	│	4.0
713	95 Est.[3]	9.4	T.F.	↓	5.5
714	95 Est.	11.4	T.F.	3 hrs.	5.5

(continued)

TABLE 14 (continued)

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
716	94 Est.	10.5	T.F.	3 hrs.	6.5
718	96 Est.	10.0	T.F.	↑	4.0
720	97 Est.	10.6	T.F.		3.5
721	96 Est.	10.6	T.F.		4.0
724	94 Est.	11.0	T.F.		6.0
726	96 Est.	10.0	2920		4.5
731	95 Est.	10.7	T.F.		5.5
732	94 Est.	10.4	T.F.		6.0
733	94 Est.	10.5	T.F.		6.0
734	96 Est.	10.7	T.F.		4.5
746	94 Est.	11.1	2850	↓	6.0
747	94 Est.	10.1	2920	3 hrs.	6.0
832	24 Est.[4]	12.5	2970	36 days	N.M.[5]
835	↑	12.0	2910	↑	82.5
836		11.3	3010		76.0
837		11.3	2880		76.0
838		11.8	2690		80.5
839		10.1	3090		81.0
840		11.1	2910		N.M.
841		10.6	2830		N.M.
842		10.7	2810		N.M.
843		12.0	T.F.		74.0
844		12.5	T.F.		78.5
845		11.6	T.F.		80.5
846		12.0	T.F.		79.0
847		11.8	T.F.		78.5
848	↓	10.9	T.F.	↓	N.M.
849	24 Est.	12.0	T.F.	36 days	N.M.

(continued)

TABLE 14 (continued)

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
850	24 Est.	11.1	T.F.	36 days	N.M.
851	↑	10.6	T.F.	↑	N.M.
852		12.0	T.F.		N.M.
853	↓	11.8	T.F.	↓	N.M.
854	24 Est.	10.9	T.F.	36 days	N.M.
675	0	9.4	3040	oven dried	N.A.
677	↑	10.6	2560	↑	↑
678		11.3	2690		
679		9.7	2530		
681		10.0	2770		
682		10.4	3050		
703		12.2	T.F.		
704		11.3	T.F.		
705		11.4	T.F.		
706		10.2	T.F.		
707		9.7	2880		
708		10.9	T.F.		
737		10.0	2970		
738		10.6	2480		
739	↓	10.6	2740	↓	↓
740	0	11.3	2580	oven dried	N.A.

1. Not applicable.
2. Specimen was tested in fatigue.
3. This value is estimated. See Table 15a for calculations which establish this estimate.
4. This value is estimated. See Table 15b for calculations which establish this estimate.
5. No measurement was made.

TABLE 15a

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 3-HOUR AIR-DRIED 0.70 w/c NATURAL AGGREGATE CONCRETE

Specimen Number	Air-Dry Water Loss (gm.)	Additional Water Loss by Oven Drying (gm.)	Total Water Loss (gm.)
698	5.5	90.5	96.0
699	3.5	96.5	100.0
700	3.0	101.0	104.0
701	3.0	102.0	105.0
702	3.5	102.0	105.5
712	4.0	109.0	113.0

Average total water loss for the six specimens = 104 gm.

$$\text{Estimated degree of saturation} = \frac{104 - \text{Air-Dry Water Loss}}{104} \times 100$$

TABLE 15b

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 36-DAY AIR-DRIED 0.70 w/c NATURAL AGGREGATE CONCRETE

Specimen Number	Air-Dry Water Loss (gm.)	Additional Water Loss by Oven Drying (gm.)	Total Water Loss (gm.)
835	82.5	not measured	
836	76.0	↑	Assumed
837	76.0		equal to
838	80.5		104 gm.
839	81.0		(Table 15a)
843	74.0		
844	78.5		
845	80.5		
846	79.0	↓	
847	78.5	not measured	

Average air-dry water loss for ten specimens = 78.6 gms.

$$\text{Estimated degree of saturation} = \frac{104 - 78.6}{104} \times 100 = 24\%$$

TABLE 16

DATA SUMMARY FOR 0.45 w/c NATURAL AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
544	100	8.4	3860	0 hrs.	N.A.[1]
545	↑	9.4	4550	↑	↑
546		10.0	4700		
547		9.6	4680		
548		9.2	4370		
549		8.8	4850		
566		8.0	T.F.[2]		
567		9.2	T.F.		
575		9.8	T.F.		
576		10.0	T.F.		
577		11.3	T.F.		
579		9.7	T.F.		
584		8.8	T.F.		
585		9.6	T.F.		
594		7.5	T.F.		
599		7.1	T.F.		
606		10.0	T.F.		
631		9.4	4050		
632		7.5	4580		
635		9.1	4720		
636		8.8	4920		
665		10.0	4210		
666	↓	10.7	3920	↓	↓
667	100	9.8	4370	0 hrs.	N.A.

(continued)

TABLE 16 (continued)

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
586	94	10.0	4160	3 hrs.	5.0
587	94	10.7	4030	↑	5.0
590	95	10.0	4070	│	4.0
591	94	9.2	4410	│	5.0
595	94	7.1	4860	│	5.0
596	94	7.3	4770	│	5.0
604	97 Est.[3]	8.4	T.F.	│	3.0
605	95 Est.	9.0	T.F.	│	4.0
610	94 Est.	8.0	T.F.	│	5.0
611	93 Est.	8.8	T.F.	│	6.0
615	94 Est.	9.6	T.F.	│	5.0
616	95 Est.	10.0	T.F.	│	4.0
621	94 Est.	8.6	T.F.	│	5.0
622	94 Est.	8.0	T.F.	│	5.0
625	97 Est.	8.2	T.F.	│	3.0
626	97 Est.	8.6	T.F.	│	3.0
627	94 Est.	9.4	T.F.	│	5.0
628	97 Est.	9.2	4550	│	3.0
639	94 Est.	8.6	4870	│	5.0
640	93 Est.	8.8	4790	│	6.0
670	97 Est.	9.0	4130	│	2.5
671	95 Est.	8.4	4250	↓	4.5
672	94 Est.	10.0	3710	3 hrs.	5.0

(continued)

TABLE 16 (continued)

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
804	47 Est.[4]	9.0	5310	35 days	49.0
805	↑	6.7	6520	↑	48.0
806		6.7	6350		49.5
807		6.7	5730		47.0
808		6.7	6440		N.M.[5]
809		6.9	5540		N.M.
810		7.5	6400		N.M.
811		8.2	6180		N.M.
812		7.5	6190		N.M.
813		7.1	5840		N.M.
815		6.3	6740		43.5
816		5.0	T.F.		43.0
817		6.3	T.F.		N.M.
818		4.8	T.F.		N.M.
820		7.1	T.F.		43.5
821		7.1	T.F.		42.5
822		7.7	T.F.		45.5
823		6.3	T.F.		N.M.
824		7.3	T.F.		N.M.
825		7.1	T.F.		N.M.
826	↓	6.9	T.F.	↓	N.M.
827	47 Est.	7.1	T.F.	35 days	N.M.

(continued)

TABLE 16 (continued)

Specimen Number	Degree of Saturation at Time of Test (%)	Air Content (%)	28 Day Static Compressive Strength (psi)	Length of Air Drying Period	Air-Dry Water Loss (gm.)
561	0	8.0	5180	oven dried	N.A.
562	↑	6.7	5040	↑	↑
563	│	7.8	5070	│	│
569	│	9.2	4350	│	│
570	│	8.8	4590	│	│
571	│	8.0	4440	│	│
653	↓	10.0	3580	↓	↓
661	0	8.4	4150	oven dried	N.A.

1. Not applicable.

2. Specimen was tested in fatigue.

3. This value is estimated. See Table 17a for calculations which establish this estimate.

4. This value is estimated. See Table 17b for calculations which establish this estimate.

5. No measurement was made.

TABLE 17a

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 3-DAY AIR-DRIED 0.45 w/c NATURAL AGGREGATE CONCRETE

Specimen Number	Air-Dry Water Loss (gm.)	Additional Water Loss by Oven Drying (gm.)	Total Water Loss (gm.)
586	5.0	78.0	83.0
587	5.0	82.0	87.0
590	4.0	84.0	88.0
591	5.0	84.0	89.0
595	5.0	78.0	83.0
596	5.0	82.0	87.0

Average total water loss for the six specimens = 86 gm.

$$\text{Estimated degree of saturation} = \frac{86 - \text{Air-Dry Water Loss}}{86} \times 100$$

TABLE 17b

DETERMINATION OF ESTIMATED DEGREE OF SATURATION FOR 35-DAY AIR-DRIED 0.45 w/c NATURAL AGGREGATE CONCRETE

Specimen Number	Air-Dry Water Loss (gm.)	Additional Water Loss by Oven Drying (gm.)	Total Water Loss (gm.)
804	49.0	not measured	Assumed equal to 86 gm. (Table 17a)
805	48.0	↑	
806	49.5		
807	47.0		
815	43.5		
816	43.0		
819	45.5		
820	43.5		
821	42.5	↓	
822	45.5	not measured	

Average air-dry water loss for ten specimens = 45.7 gm.

$$\text{Estimated degree of saturation} = \frac{86 - 45.7}{86} \times 100 = 47\%$$

TABLE 18

DATA SUMMARY FOR 0.70 w/c SYNTHETIC AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength (psi)	Synthetic Aggregate Designation
765	100	1940	A-1
766	↑	1900	↑
767		1970	
768		2000	
769		1910	
770		T.F.[1]	
771		T.F.	
772		T.F.	↓
773		T.F.	A-1
783		2640	A-2
784		2900	↑
785		2930	
786		2870	
787		2780	
788		2960	
789		T.F.	
791		T.F.	
792		T.F.	
793		T.F.	
794	↓	T.F.	↓
795	100	2890	A-2

1. Specimen was tested in fatigue.

TABLE 19

DATA SUMMARY FOR 0.45 w/c SYNTHETIC AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation at Time of Test (%)	28 Day Static Compressive Strength (psi)	Synthetic Aggregate Designation
753	100	3520	A-1
754		3550	
755		3590	
756		3660	
757		3750	
758		T.F.[1]	
760		T.F.	
761		T.F.	
762		T.F.	
763		T.F.	A-1
778		5100	A-2
779		4910	
780		4880	
781		4940	
782		4830	
796		5020	
797		T.F.	
798		T.F.	
799		T.F.	
800		T.F.	
801		5270	
802		T.F.	A-2
728		6100	A-3
729		6400	
730		6430	
741		5860	
742		6060	
743		6000	
744		T.F.	
745		T.F.	
748		T.F.	
749		T.F.	
750		T.F.	
751		5770	
752	100	5490	A-3

1. Specimen was tested in fatigue.

TABLE 20

FATIGUE DATA FOR 0.70 w/c NATURAL AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
690	100	16,300 (81.1)[1]	900 (4.5)[1]	6,100
691	↑	16,000 (79.6)	1000 (5.0)	1,900
692		16,300 (81.1)	1000 (5.0)	1,300
693		16,500 (82.0)	1000 (5.0)	6,400
694		16,200 (80.6)	900 (4.5)	2,700
695		14,200 (70.7)	1000 (5.0)	12,500
696		14,000 (69.6)	1000 (5.0)	14,800
697		14,300 (71.1)	1100 (5.0)	10,100
709	↓	14,300 (71.1)	1000 (5.0)	19,800
710	100	14,300 (71.1)	1000 (5.0)	5,600
713	95	16,600 (81.0)[2]	1300 (6.4)[2]	1,400
714	95	16,500 (80.4)	1400 (6.8)	3,600
716	94	16,500 (80.4)	1400 (6.8)	4,100
718	96	16,600 (81.0)	1300 (6.4)	3,700
720	97	14,500 (70.6)	800 (3.9)	28,800
721	96	16,500 (80.4)	1400 (6.8)	4,000
724	94	14,500 (70.6)	1000 (4.9)	11,100
731	95	14,500 (70.6)	1000 (4.9)	10,800
732	94	14,500 (70.6)	1000 (4.9)	23,100
733	94	14,500 (70.6)	1000 (4.9)	2,000
734	96	14,500 (70.6)	1000 (4.9)	5,900
843	24	14,100 (69.5)[3]	800 (3.9)[3]	294,700
844	↑	14,100 (69.5)	700 (3.4)	168,400
845		14,300 (70.5)	1000 (4.9)	30,800
846		14,000 (69.0)	900 (4.4)	84,900
847	↓	14,100 (69.5)	900 (4.4)	90,600
848	24	14,300 (70.5)	1000 (4.9)	481,300

(continued)

TABLE 20 (continued)

Specimen Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
849	24	16,300 (80.4)	1000 (4.9)	3,200
850	↑	16,800 (82.8)	600 (2.9)	11,000
851	│	16,800 (82.8)	800 (3.9)	20,200
852	│	16,300 (80.4)	900 (4.4)	2,700
853	↓	16,200 (79.9)	900 (4.4)	7,000
854	24	16,400 (80.8)	600 (2.9)	34,100
703	0	15,000 (77.9)[4]	1000 (5.2)[4]	16,500
704	↑	15,000 (77.9)	1000 (5.2)	15,600
705	│	15,500 (80.5)	1000 (5.2)	112,200
706	↓	15,000 (77.9)	1500 (7.8)	11,800
708	0	15,500 (80.5)	1000 (5.2)	128,600

1. Figure in parentheses for specimens 690 through 710 is the fatigue load expressed as a percentage of the average compressive strength of 9 saturated specimens (Y_{avg} = 2875 psi.).

2. Figure in parentheses for specimens 713 through 734 is the fatigue load expressed as a percentage of the average compressive strength of 9 air-dried specimens (Y_{avg} = 2931 psi.).

3. Figure in parentheses for specimens 843 through 854 is the fatigue load expressed as a percentage of the average compressive strength of 9 air-dried specimens (Y_{avg} = 2900 psi.).

4. Figure in parentheses for specimens 703 through 708 is the fatigue load expressed as a percentage of the average compressive strength of 11 oven-dried specimens (Y_{avg} = 2754 psi.).

TABLE 21

FATIGUE DATA FOR 0.45 w/c NATURAL AGGREGATE CONCRETE SPECIMENS

Specimen Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
566	100	22,500 (72.5)[1]	1600 (5.2)[1]	3,000
567	↑	22,200 (71.5)	1500 (4.8)	3,600
575		22,000 (70.8)	1000 (3.2)	2,000
576		22,200 (71.5)	1200 (3.9)	3,500
577		22,200 (71.5)	1200 (3.9)	1,700
579		19,500 (62.8)	1300 (4.2)	9,000
584		19,300 (62.2)	1500 (4.8)	46,500
585		19,600 (63.2)	1300 (4.2)	39,600
594		19,600 (63.2)	1300 (4.2)	33,800
599	↓	19,800 (63.8)	1200 (3.9)	192,200 → [2]
606	100	19,500 (62.8)	1300 (4.2)	11,500
604	97	21,300 (69.4)[3]	1100 (3.6)[3]	115,700
605	95	21,700 (70.6)	1000 (3.3)	17,800
610	94	21,700 (70.6)	900 (2.9)	104,400
611	93	21,700 (70.6)	1100 (3.6)	46,900
615	94	21,600 (70.4)	1200 (3.9)	27,000
616	95	21,500 (70.0)	1100 (3.6)	6,800
621	94	24,500 (79.7)	1200 (3.9)	3,900
622	94	25,000 (81.4)	700 (2.3)	7,100
625	97	24,500 (79.7)	900 (2.9)	6,200
626	97	25,000 (81.4)	500 (1.6)	5,200
627	94	24,500 (79.7)	800 (2.6)	2,200
816	47	30,000 (70.1)[4]	1200 (2.8)[4]	460,300 → [5]
817	47	29,500 (69.0)	1000 (2.3)	222,700
818	47	30,000 (70.1)	1200 (2.8)	910,000 → [6]
820[7]	47	34,000 (79.5)	1200 (2.8)	31,600

TABLE 21 (continued)

Specimen Number	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
821[7]	47	34,500 (80.6)	1500 (3.5)	3,000
822[7]	↑	33,800 (79.0)	1800 (4.2)	4,200
823[7]	│	29,500 (69.0)	1500 (3.5)	183,300
824[7]	│	34,500 (80.6)	1500 (3.5)	2,200
825[7]	│	34,000 (79.5)	1800 (4.2)	22,800
826[7]	↓	30,000 (70.1)	1000 (2.3)	260,400
827[7]	47	30,000 (70.1)	1500 (3.5)	163,300

1. Figure in parentheses for specimens 566 through 606 is the fatigue load expressed as a percentage of the average compressive strength of 13 saturated specimens (Y_{avg} = 4437 psi.).

2. Specimen was removed from fatigue machine and tested statically. The maximum fatigue load based on this static strength is 54 percent.

3. Figure in parentheses for specimens 604 through 627 is the fatigue load expressed as a percentage of the average compressive strength of 12 air-dried specimens (Y_{avg} = 4383 psi.).

4. Figure in parentheses for specimens 816 through 827 is the fatigue load expressed as a percentage of the average compressive strength of 11 air-dried specimens (Y_{avg} = 6113 psi.).

5. Machine broke down before specimen had failed.

6. Specimen had not failed when machine was stopped.

7. Specimen was tested 10 days after intended time because of a machine breakdown. A weight check indicated no significant loss of water from specimen during the 10 day period.

TABLE 22

FATIGUE DATA FOR 0.70 w/c SYNTHETIC AGGREGATE CONCRETE SPECIMENS

Specimen Number	Synthetic Aggregate Designation	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
770	A-1	100	9,500 (69.8)[1]	1000 (7.4)[1]	11,200
771	↑	↑	9,300 (68.4)	1100 (8.1)	11,700
772	↓		9,500 (69.8)	1200 (8.8)	12,900
773	A-1		9,500 (69.8)	1200 (8.8)	13,800
789	A-2		14,000 (70.2)[2]	1000 (5.0)[2]	19,100
791	↑		14,000 (70.2)	1000 (5.0)	9,000
792			13,900 (69.7)	1100 (5.5)	8,300
793	↓	↓	14,000 (70.2)	1000 (5.0)	9,000
794	A-2	100	13,900 (69.7)	1100 (5.5)	15,100

1. Figure in parentheses for specimens 770 through 773 is the fatigue load expressed as a percentage of the average compressive strength of 5 saturated specimens (Y_{avg} = 1944 psi.).

2. Figure in parentheses for specimens 789 through 794 is the fatigue load expressed as a percentage of the average compressive strength of 7 saturated specimens (Y_{avg} = 2853 psi.).

TABLE 23

FATIGUE DATA FOR 0.45 w/c SYNTHETIC AGGREGATE CONCRETE SPECIMENS

Specimen Number	Synthetic Aggregate Designation	Degree of Saturation (%)	Maximum Fatigue Load (lbs.)	Minimum Fatigue Load (lbs.)	Number of Stress Cycles Endured
758	A-1	100	18,000 (71.2)[1]	1000 (4.0)[1]	6,500
760	↑	↑	18,000 (71.2)	1000 (4.0)	11,100
761	│	│	18,000 (71.2)	1000 (4.0)	14,100
762	↓	│	18,000 (71.2)	1000 (4.0)	11,300
763	A-1	│	18,000 (71.2)	1000 (4.0)	10,500
797	A-2	│	25,000 (71.6)[2]	800 (2.3)[2]	11,600
798	↑	│	25,000 (71.6)	900 (2.6)	10,300
799	│	│	25,500 (73.0)	1000 (2.9)	11,900
800	↓	│	25,500 (73.0)	1000 (2.9)	8,600
802	A-2	│	25,500 (73.0)	1000 (2.9)	12,700
744	A-3	│	31,500 (74.8)[3]	1000 (2.4)[3]	5,100
745	↑	│	31,000 (73.7)	1000 (2.4)	3,300
748	│	│	32,000 (76.0)	800 (1.9)	300
749	↓	↓	31,500 (74.8)	1000 (2.4)	4,000
750	A-3	100	31,500 (74.8)	1200 (2.9)	1,800

1. Figure in parentheses for specimens 758 through 763 is the fatigue load expressed as a percentage of the average compressive strength of 5 saturated specimens (Y_{avg} = 3614 psi.).

2. Figure in parentheses for specimens 797 through 802 is the fatigue load expressed as a percentage of the average compressive strength of 7 saturated specimens (Y_{avg} = 4993 psi.).

3. Figure in parentheses for specimens 744 through 750 is the fatigue load expressed as a percentage of the average compressive strength of 8 saturated specimens (Y_{avg} = 6014 psi.).

APPENDIX C

STATISTICAL ANALYSES

TABLE 24

SIGNIFICANCE OF DIFFERENCE TEST FOR COMPARISON OF 0.70 w/c PASTE SPECIMENS MADE BY OPERATORS A AND B

Operator A: $n = 31$ $\quad \bar{Y} = 3652$ psi $\quad s^2 = 64{,}900$ psi^2

w/c = 0.70 $\quad$ degree of saturation = 100%

Operator B: $n = 9$ $\quad \bar{Y} = 3734$ psi $\quad s^2 = 141{,}100$ psi^2

w/c = 0.70 $\quad$ degree of saturation = 100%

<u>Test on Variability</u>

H_o: $\sigma_1^2 = \sigma_2^2$ $\qquad s_1^2 = 141{,}100 \qquad s_2^2 = 64{,}900$

H_1: $\sigma_1^2 > \sigma_2^2$

$\alpha = 5\%$

$$F_{obs} = \frac{141{,}100}{64{,}900} = 2.18 \qquad F_{(.95)\ (8,\ 30)} = 2.27$$

$2.27 > 2.18 \ \therefore$ accept H_o

<u>Test on Means</u>

H_o: $\mu_1 = \mu_2$ $\qquad \bar{Y}_1 = 3734 \qquad \bar{Y}_2 = 3652$

H_1: $\mu_1 > \mu_2$

$\alpha = 5\%$

$$s_{\bar{y}_1 - \bar{y}_2} = \sqrt{\left[\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}\right]\left[\frac{1}{n_1} + \frac{1}{n_2}\right]} = 107$$

$$t_{obs} = \frac{3734 - 3652}{107} = 0.77 \qquad t_{(.05)\ (38)} = 1.68$$

$1.68 > 0.77 \ \therefore$ accept H_o

TABLE 25

SIGNIFICANCE OF DIFFERENCE TEST FOR COMPARISON OF 0.70 w/c PASTE SPECIMENS MADE BY OPERATORS A, B, AND C

Operator A and B (pooled): $n = 40$ $\bar{Y} = 3671$ psi $s^2 = 80{,}110$ psi^2

w/c = 0.70 degree of saturation = 100%

Operator C: $n = 14$ $\bar{Y} = 3248$ psi $s^2 = 9{,}800$ psi^2

w/c = 0.70 degree of saturation = 100%

Test on Variability

H_o: $\sigma_1^2 = \sigma_2^2$ $s_1^2 = 80{,}110$ $s_2^2 = 9{,}800$

H_1: $\sigma_1^2 > \sigma_2^2$

$\alpha = 5\%$

$$F_{obs} = \frac{80{,}110}{9{,}800} = 8.16 \qquad F_{(.95)\ (39,\ 13)} = 2.35$$

$2.35 < 8.16$ ∴ reject H_o, accept H_1

Test on Means

H_o: $\mu_1 = \mu_2$ $\bar{Y}_1 = 3671$ $\bar{Y}_2 = 3248$

H_1: $\mu_1 > \mu_2$

$\alpha = 5\%$

$$t_{obs} = \frac{3671 - 3248}{\sqrt{\frac{80{,}110}{40} + \frac{9{,}800}{14}}} = 8.16$$

$$t' = \frac{\left(\frac{80{,}110}{40}\right) t_1 + \left(\frac{9{,}800}{14}\right) t_2}{\left(\frac{80{,}110}{40}\right) + \left(\frac{9{,}800}{14}\right)} = 1.70$$

where $t_1 = t_{(.05)\ (39)} = 1.68$

$t_2 = t_{(.05)\ (13)} = 1.76$

$1.70 < 8.16$ ∴ reject H_o, accept H_1

TABLE 26

TYPICAL LINEAR REGRESSION ANALYSIS

The calculations that follow are for the determination of the least squares line for the fatigue data of the saturated 0.70 water-cement ratio paste specimens. Only those specimens that failed are considered. All the other fatigue data for the cement pastes and the concretes were handled by an identical procedure.

S	n(=$\log_{10}N$)
51.2	5.94161
62.5	5.25600
62.5	5.02653
63.3	5.73687
61.6	5.52284
72.9	4.35411
73.7	3.94939
73.7	4.00000
71.1	4.24551
72.0	4.50786
83.4	2.84510
84.4	3.17609
86.4	2.84510
85.4	2.90309
86.4	3.30103

$$\bar{S} = \frac{\Sigma(S_i)}{m} = \frac{1090.5}{15} = 72.70$$

$$\bar{n} = \frac{\Sigma(n_i)}{m} = \frac{63.61113}{15} = 4.240742$$

$$x_i = S_i - \bar{S} \qquad y_i = n_i - \bar{n}$$

$$b = \frac{\Sigma(x_i\, y_i)}{\Sigma(x_i{}^2)} = \frac{-160.427249}{1675.04} = -0.0958$$

$$\widehat{\log_{10}N} = a + b\,(S)$$

$$\text{where } a = \bar{n} - (b)\bar{S}$$

$$\therefore\ \widehat{\log_{10}N} = 11.2054 - 0.0958\,(S)$$

VITA

VITA

John deCourcy Antrim was born in Jersey City, New Jersey on February 9, 1934. He received his primary and secondary education in public schools in New Jersey and a private school in Brazil, and was graduated from Millburn (N.J.) High School in 1952.

Mr. Antrim received the BSCE degree from Lehigh University in 1956 and the MSCE degree from Purdue University in 1958. He was then employed by Harland Bartholomew and Associates in their Memphis, Tennessee office from July 1958 until January 1959. He then returned to Purdue University as a research assistant with the Joint Highway Research Project and as an instructor in the School of Civil Engineering.

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"Fatigue Study of Air-Entrained Concrete," Proceedings, American Concrete Institute, Vol. 55, pp. 1173-1182, 1958-59. Co-authored with J. F. McLaughlin.

"Fatigue Properties of Lightweight Aggregate Concrete," Proceedings, American Concrete Institute, Vol. 58, pp. 149-162, 1961-62. Co-authored with W. H. Gray and J. F. McLaughlin.