The Mechanism of Fatigue in Cement Paste and Plain Concrete

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An investigation was conducted to determine the fatigue behavior of cement paste loaded in axial compression and the fatigue behavior of the paste when it is diluted with aggregate.

Cement pastes 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 concretes containing synthetic aggregates. Cylindrical specimens, 2 in. in diameter by 4 in. in height, were used for evaluating the cement pastes and cylindrical specimens, 3 in. in diameter by 6 in. in height, were used for evaluating the concretes. Specimens were tested in a saturated condition and at moisture contents less than that at saturation. Over 500 specimens were tested statically in unconfined compression and over 150 specimens were tested dynamically in unconfined compression at specific stress levels at a speed of 1,000 cpm.

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.

•ONE area of portland cement concrete technology that has been 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 it has only been during the past ten years that the mechanism of fatigue has received attention. It is the purpose of this paper to review only the work done towards determining the mechanism of fatigue in plain concrete. For a comprehensive review of published information on the fatigue properties of plain concrete, it is suggested that Nordby's (1) or Murdock's (2) review be consulted.

Murdock and Kesler (3) studied the effect of coarse aggregate by inserting single, preshaped limestone aggregates in the tension zone of mortar flexure specimens. Each coarse aggregate piece extended the full width of the test specimen so as to make the problem essentially a two-dimensional one and the orientation of the aggregate cross section, as well as the proximity of its outer surface to the free tension surface of the specimen, was varied from one test series to another. Static and fatigue flexure tests of plain mortar specimens and mortar specimens containing coarse aggregate inclusions gave sufficient data to form an hypothesis that attributes the initiation of fatigue failure

Paper sponsored by Committee on Mechanical Properties of Concrete and presented at the 46th Annual Meeting.

to the progressive deterioration of the bond between coarse aggregate and the binding matrix.

Doyle, Kung, Murdock, and Kesler (4) studied the flexural 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 Murdock and Kesler study, however, this time the aggregates were cylindrical pieces of aluminum or granite and the preformed voids were 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 (5) 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 the prevously mentioned studies except that all the testing was conducted on saturated specimens (previous specimens were air-dried). Aggregate pieces were again cylindrical and were either of granite or limestone. Their conclusions were (a) fatigue failure begins in the bond between the coarse aggregate and the mortar matrix and apparently is not influenced by the elastic modulus of the coarse aggregate, 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.

Glucklich (6) 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 predetermined 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.

The author (7) conducted an investigation which was concerned first with the fatigue behavior of cement paste loaded in axial compression, and second, with the fatigue behavior of cement paste diluted with aggregate.

SCOPE

The fatigue behavior of cement paste was investigated with respect to the effect of the structure of the hardened paste and the effect of the moisture content of the paste. 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. Moisture contents selected were 100 percent of saturation and approximately 95 percent of saturation. Saturation moisture content was taken as the moisture content of the specimen upon removal of the specimen from the curing water. Moisture contents below saturation are average moisture contents estimated from specimen weight changes occurring after removal from the curing water. Moisture contents below 90 percent for the low water-cement ratio cement paste specimens were not practical because of specimen cracking.

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. In addition, the effect of the aggregate strength was investigated 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 other characteristics of the aggregates used and this was accomplished by manufacturing the aggregates in the laboratory. The manufacturing process was simply one of crushing hardened cement pastes of known strengths, sieving, and then recombining to give an aggregate with a predetermined gradation.

SPECIMEN MANUFACTURE

A procedure was developed for making one specimen at a time and which allowed successive specimens to be made in an identical manner, the result being a low mix to mix variation for a given mix design. The procedure used to make cement paste specimens, 2 in. in diameter by 4 in. in height, was to make two specimens each day, allow them to wet 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. Saturated specimens tested in fatigue were kept wet by wrapping specimen with wet absorbent cotton followed by polyethylene film. Air-dried specimens were wrapped with polyethylene film to prevent further loss of moisture during the fatigue testing.

Test specimens for the paste-aggregate combinations were prepared one at a time and in an identical manner although upwards to 12 specimens, 3 in. in diameter by 6 in. in height, were made each day. As with the cement paste specimens, the concrete specimens were cured for 28 days in a saturated lime solution. Testing format was

TABLE 1

AGGREGATE CHARACTERISTICS

Physical Properties	
Limestone coarse aggregate	
Dry rodded unit weight	94 pcf
Bulk specific gravity	2.66
Absorption	0.72%
River terrace sand fine aggregate	
Bulk specific gravity	2.66
Absorption	1.28%
A-1 Aggregate (w/c = 0.85)	
Dry rodded unit weight	55 pcf
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 pcf
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 pcf
Bulk specific gravity	1.77
Absorption	18.6%
Approximate compressive strength	13,000 psi

Gradation
(Natural and Synthetic Aggregate)

Coarse Aggregate Fraction		Finer Aggregate Fraction	
Sieve Size	Percent Finer	Sieve Size	Percent Finer
1/2 in.	100	No. 4	100
3/8 in.	55	No. 8	90
No. 4	0	No. 16	67
		No. 30	42
		No. 50	20
		No. 100	6
		Fineness modulus	2.75

TABLE 2

STATIC STRENGTH CHARACTERISTICS OF CEMENT PASTE TEST SPECIMENS

Uncorrected w/c (lb/lb)	Operator	n	$\overline{Y}$ (psi)	C (%)	S (%)	Air Drying Time
0.70	1, 2	40	3671	7.7	100	
	3	14	3248	3.1	100	
	3	6	3538	4.3	96	4½ hr
0.45	3	17	9630	3.7	100	
	3	6	10878	2.6	91	3 days

where n = the number of test specimens,
$\overline{Y}$ = the average compressive strength of the test specimens,
C = the coefficient of variation for the test specimen strengths,
S = the approximate average degree of saturation (at time of removal from the curing water, specimens were assumed to be in a saturated condition).

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. The paste-aggregate combination that used natural aggregates had limestone as the coarse aggregate and sand as the fine aggregate. The three synthetic aggregates were similar in particle size, particle shape, and gradation (fine through coarse fraction); and they were different in strength and porosity. 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 them, are given in Table 1 along with the characteristics of the natural aggregates.

All cement paste specimens and concrete specimens were made with a Type I portland cement from a single clinker batch.

CEMENT PASTE TESTS

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. The strength data for the two cement paste mixes are summarized in Table 2. Two sets of data are shown for the 0.70 w/c cement paste at 100 percent of saturation because a statistical analysis showed that it was necessary to treat the two groupings separately. The difference was attributed to operator technique in making the specimens since all operations, other than making the specimens, were performed by operator 3.

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 an S-N curve, it was not deemed necessary to conduct the testing at numerous load levels.

All the fatigue tests were started at the age of 28 days for the saturated specimens and immediately after the completion of drying for the air-dried specimens. 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.

All fatigue specimens were tested in the Krouse-Purdue axial-load fatigue machine which 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 machine has a capacity of ±60,000 lb and operates at 1,000 cpm. Loads are measured to within ±100 lb 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 which holds the test specimen in place.

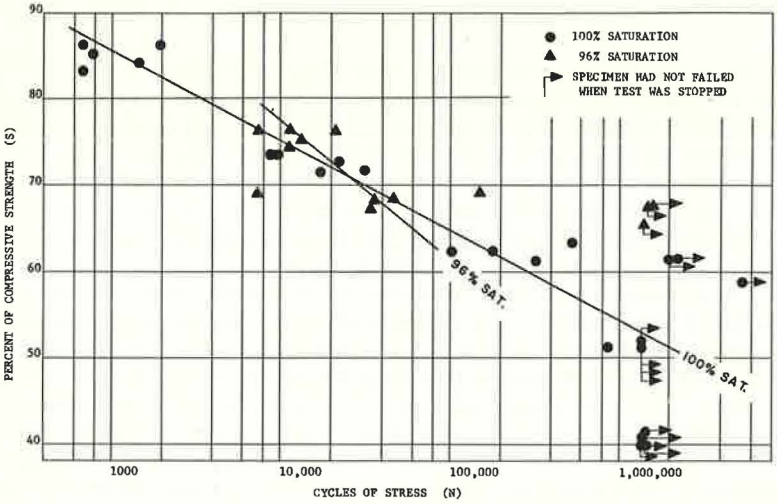

Figure 1. S-N diagram for 0.70 w/c cement paste.

The fatigue test data for both cement paste mixes are shown in Figures 1 and 2. The fitting of a straight line to the data of each grouping was 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 ($\log_{10}N$) are normally distributed (8). 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 were 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.

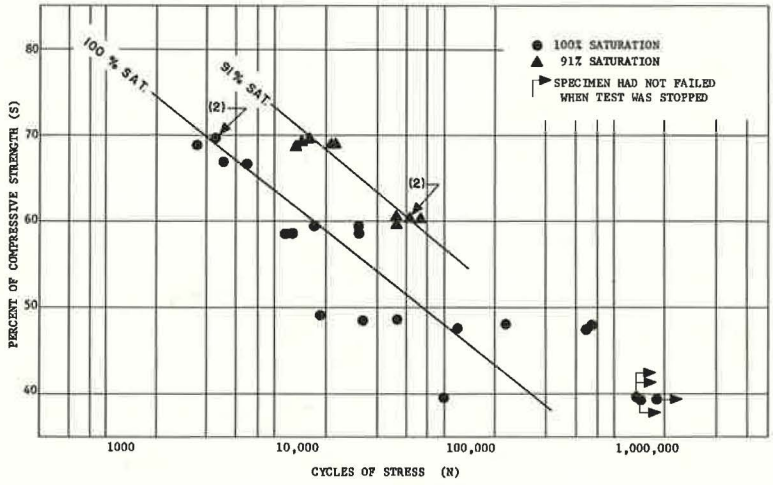

Figure 2. S-N diagram for 0.45 w/c cement paste.

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.

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 borne 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 change in strength caused by reducing the moisture content of the hardened paste can be explained by the presence of shrinkage stresses in the cement paste. Powers (9) 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, thus 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 was clearly evident in this investigation. The presence of shrinkage stresses in the air-dried 0.45 w/c paste specimens is indicated by the need to apply an additional compressive load (Table 2) to overcome the tensile stresses which develop as the water is withdrawn. 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 $4\frac{1}{2}$ 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.

The curves of Figures 1 and 2 have been reproduced in Figure 3 better to illustrate the fatigue behavior of the cement pastes. The S-N curve for the saturated 0.70 w/c

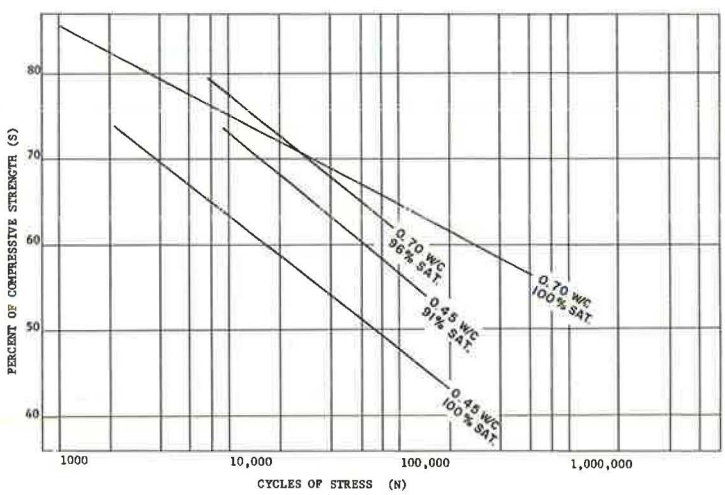

Figure 3. Graphical representation of cement paste fatigue data.

TABLE 3

PHYSICAL PROPERTIES OF THE NATURAL AGGREGATE CONCRETES

w/c (lb/lb)	Degree of Saturation (%)	Air Drying Time	Number of Specimens	Average Compressive Strength (psi)	Strength Coefficient of Variation (%)	Average Air Content** (%)	Air Content Coefficient of Variation (%)
0.70	100		9	2,875	3.1	11.0	8.5
	95	3 hr	9	2,931	4.5	10.6	5.9
	24	5 wk	9	2,900	4.1	11.3	6.6
	0	—*	11	2,754	7.5	10.3	6.1
0.45	100		13	4,437	7.8	9.3	8.7
	95	3 hr	12	4,383	8.8	9.0	12.1
	47	5 wk	11	6,113	7.3	7.2	11.1
	0	—*	8	4,550	11.9	8.4	11.8

*Oven dried at 220 F to constant weight.

**The natural aggregate concrete was an air-entrained concrete because earlier work (8) had indicated that entrained air would decrease the variability of the fatigue data.

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 before 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; thus it is capable of readjusting its structure, and 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 3 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. Table 2 indicates that the compressive strengths 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 then they do in the static strength because they serve to restrain crack propagation.

TABLE 4

PHYSICAL PROPERTIES OF THE SYNTHETIC AGGREGATE CONCRETES

w/c (lb/lb)	Degree of Saturation (%)	Number of Specimens	Average Compressive Strength (psi)	Strength Coefficient of Variation (%)	Aggregate Designation	Approx. Aggregate Strength (psi)	Approx. Cement Paste Strength (psi)	Failure Type[a]
0.70	100	5	1,944	2.1	A-1	2,900	3,200	Bond[b]
	100	7	2,853	3.8	A-2	8,000	3,200	Bond
0.45	100	5	3,614	2.6	A-1	2,900	9,600	Bond & Aggregate[c]
	100	7	4,993	3.0	A-2	8,000	9,600	Mostly Aggregate
	100	8	6,014	5.2	A-3	13,000	9,600	Mostly Aggregate

[a]Deduced from the appearance of the fractured specimens.

[b]The bond failure referred to is at the coarse aggregate interface.

[c]The aggregate failure referred to is failure through the aggregate.

Crack propagation is an important factor in the fatigue failure of any material since final fracture is dependent on 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 (10).

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 from that in the static situation in 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 difference. 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.

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.

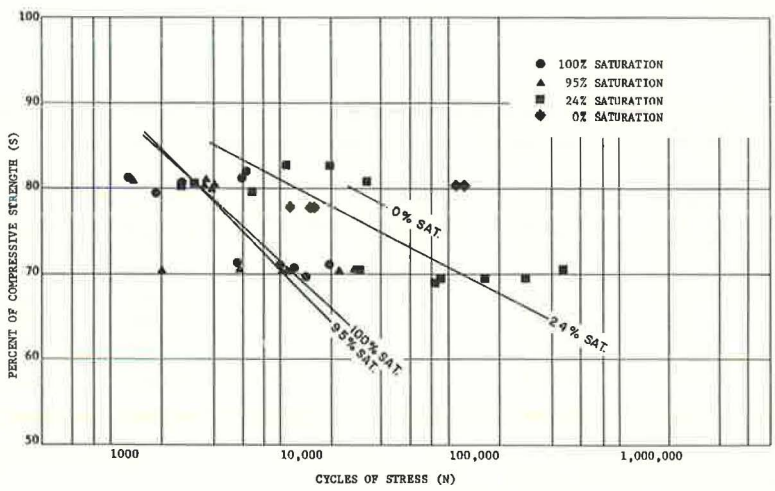

Figure 4. S-N diagram for 0.70 w/c natural aggregate concrete.

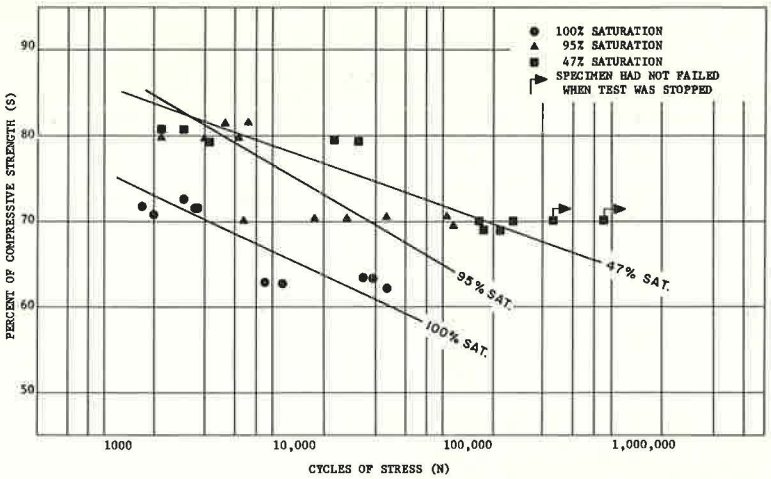

Figure 5. S-N diagram for 0.45 w/c natural aggregate concrete.

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.

PASTE-AGGREGATE COMBINATION TESTS

Static Compression Tests

The physical properties of the natural aggregate concretes are summarized in Table 3; those for the synthetic aggregate concretes are summarized in Table 4.

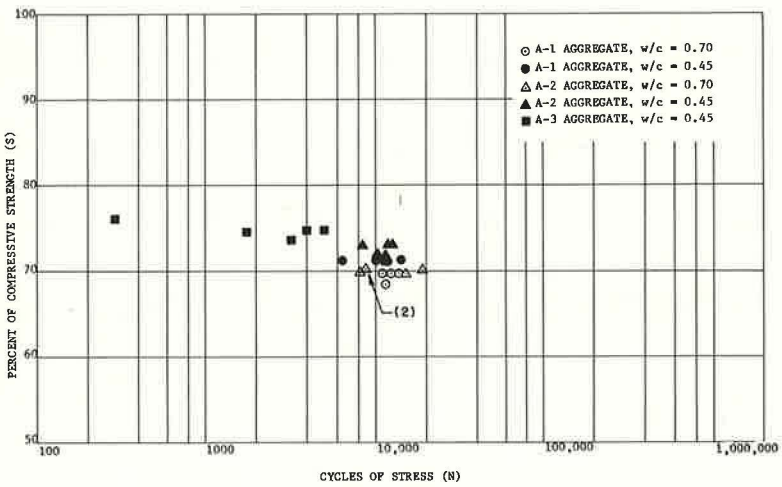

Figure 6. S-N diagram for the synthetic aggregate concretes.

TABLE 5

CEMENT PASTE AND CONCRETE STATIC STRENGTHS

w/c (lb/lb)	Degree of Saturation (%)	Approximate Compressive Strength				
		Cement Paste (psi)	Natural Aggregate Air-Entrained Concrete[a] (psi)	A-1 Aggregate Concrete[b] (psi)	A-2 Aggregate Concrete[c] (psi)	A-3 Aggregate Concrete[d] (psi)
0.70	100	3,200	2,900	1,900	2,900	
	96	3,500				
	95		2,900			
	24		2,900			
	0		2,800			
0.45	100	9,600	4,400	3,600	5,000	6,000
	95		4,400			
	91	10,900				
	47		6,100			
	0		4,600			

[a]Approximate compressive strength of limestone aggregate: 26,000 psi.
[b]Approximate compressive strength of A-1 aggregate: 2,900 psi.
[c]Approximate compressive strength of A-2 aggregate: 8,000 psi.
[d]Approximate compressive strength of A-3 aggregate: 13,000 psi.

Fatigue Tests

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.

The fatigue test data for the natural aggregate concretes and the synthetic aggregate concretes are shown in Figures 4, 5, and 6. The method of least squares was used to fit curves to those groupings where sufficient data were 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 these data. A short line in Figure 4 helps 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 logarithms of the five stress cycles to failure values. No data are shown in Figure 5 for oven-dried

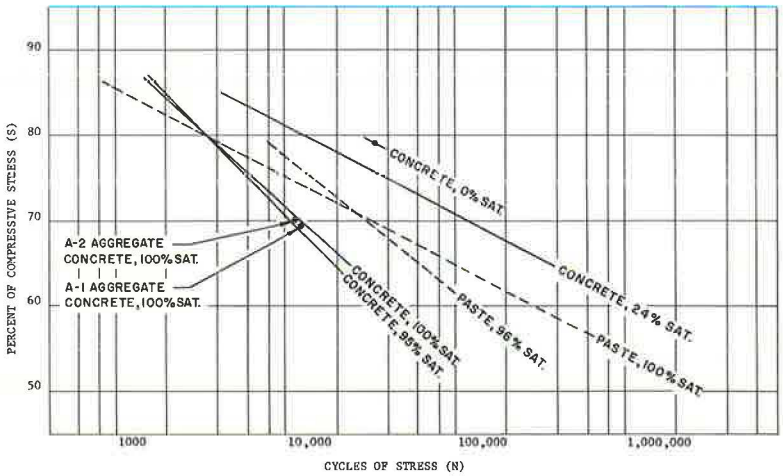

Figure 7. Graphical representation of 0.70 w/c cement paste and concrete fatigue data.

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

In Table 5, it is apparent 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. An explanation of the effect of the aggregate on the static compressive strength of the concrete is not in order for this paper; however, it has been discussed by others (11, 12).

Figures 7 and 8 indicate 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 (Fig. 3).

The natural aggregate concrete also responded to changes in moisture content in a manner similar to that of the pure cement paste. A small reduction in moisture content from 100 percent of saturation did not materially change the position of the S-N curve for the 0. 70 w/c concrete (Fig. 7). This same behavior was characteristic of the 0. 70 w/c paste. Figure 8 indicates that a small reduction in moisture content from 100 percent of saturation shifted the curves 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 7 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 0 percent of saturation resulted in an additional upwards shift of the S-N curve. Figure 8 indicates that reducing the moisture content of the 0. 45 w/c concrete from 95 percent of saturation to 47 percent of

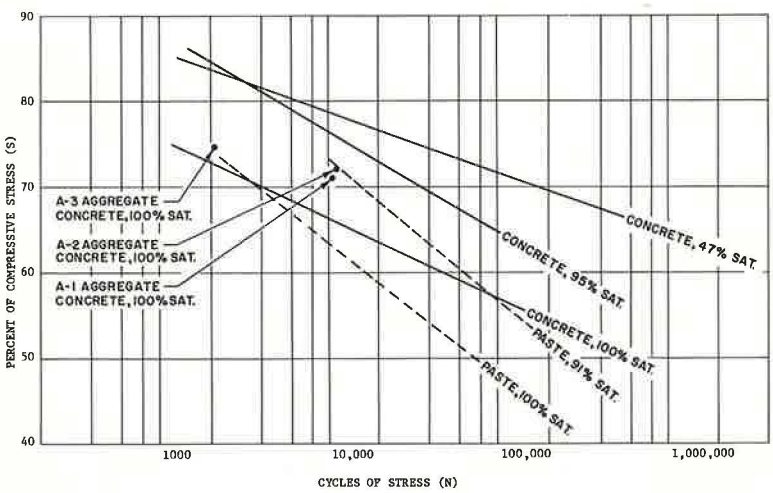

Figure 8. Graphical representation of 0.45 w/c cement paste and concrete fatigue data.

saturation resulted in an upwards shift of the S-N curve. Reducing the moisture content of the 0.45 w/c concrete to 0 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 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 0 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 7 and 8 also indicate that the aggregate, or at least its presence, has an influence on the fatigue behavior of the concrete. Figure 7 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 8 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 (Figs. 7 and 8) does not appear to be consistent with the fatigue behavior pattern established by the saturated cement pastes and the saturated natural aggregate concretes. However, it should be realized that for each specimen tested, a situation existed which involved the degree of bond between paste and aggregate, a different modulus of elasticity for paste and aggregate, and the volume ratio of paste to aggregate. Since the number of cycles to failure is dependent on the stress level, it is suggested that it is necessary to determine the stress level of the critical component by taking into account the load carrying area of the component and its modulus of elasticity. Unfortunately the data obtained in this investigation are not of the type which permits an analysis to be made along the lines suggested. (It is hoped that an explanation of this behavior will be one of the results of an investigation the author is currently conducting.)

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.
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> 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

Analysis of the results of some 150 specimens tested in fatigue indicate 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.

The fatigue behavior of the synthetic aggregate concrete suggests that several factors influence the number of cycles to failure. Apparently either the paste or the aggregate becomes the critical component in accordance with its modulus of elasticity and the volume of the component present in the concrete.

The proposed mechanism for plain concrete is different from the fatigue mechanism proposed by Murdock and Kesler (3). 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 paper 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 not clear.

A previous paper (8) revealed that entrained air does not affect the fatigue behavior of concrete, and the results of this study give no cause for disputing that 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 oven-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.

ACKNOWLEDGMENTS

The research described in this paper was conducted at Purdue University and the author is indebted to the Joint Highway Research Project for sponsoring the research, and to Dr. J. F. McLaughlin who provided the guidance.

REFERENCES

1. Nordby, G. M. Fatigue of Concrete—A Review of Research. ACI Jour., Vol. 30, No. 2 (Proc., Vol. 55), pp. 191-221, Aug. 1958.
2. Murdock, J. W. A Critical Review of Research on Fatigue of Plain Concrete. Eng. Exp. Stat. Bull. 475, Univ. of Illinois, 1965.
3. Murdock, J. W., and Kesler, C. E. The Mechanism of Fatigue Failure in Concrete. T. & A. M. Report No. 587, Univ. of Illinois, Aug. 1960.
4. Doyle, J. N., Kung, S. H. L., Murdock, J. W., and Kesler, C. E. Second Progress Report—Mechanism of Fatigue Failure in Concrete. T. & A. M. Report No. 601, Univ. of Illinois, Sept. 1961.
5. Neal, J. A., Kung, S. H. L., and Kesler, C. E. Third Progress Report—Mechanism of Fatigue Failure in Concrete. T. & A. M. Report No. 623, Univ. of Illinois, Aug. 1962.
6. Glucklich, J. The Flexural Static and Fatigue Failure of Portland Cement Mortar. T. & A. M. Report No. 622, Univ. of Illinois, Aug. 1962.
7. Antrim, J. D. A Study of the Mechanism of Fatigue in Cement Paste and Plain Concrete. Thesis, Purdue Univ., Jan. 1964.
8. Antrim, J. D., and McLaughlin, J. F. Fatigue Study of Air-Entrained Concrete. ACI Jour., Vol. 30, No. 11 (Proc., Vol. 55), pp. 1173-1182, May 1959.
9. Powers, T. C. Causes and Control of Volume Change. Jour. of the R&D Laboratories, Portland Cement Association, Vol. 1, No. 1, pp. 29-39, Jan. 1959.
10. Richards, C. W. Engineering Materials Science. Wadsworth Publishing Company, Inc., San Francisco, 1961.
11. Hsu, T. T. C., Slate, F. O., Sturman, G. M., and Winter, G. Microcracking of Plain Concrete and the Shape of the Stress-Strain Curve. ACI Jour., No. 2 (Proc., Vol. 60), pp. 209-224, Feb. 1963.
12. Alexander, K. M. Strength of the Cement-Aggregate Bond. ACI Jour., Vol. 31, No. 5 (Proc., Vol. 56), pp. 377-390, Nov. 1959.