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ABSTRACT

This report presents the state-of-the-art information on fatigue behavior of plain concrete manufactured with or without fly ash. The report includes the information on the mechanism of fatigue fracture, the factors affecting fatigue behavior, and fatigue models for plain concrete.

A number of studies have shown that concrete fatigue strength is significantly influenced by a large number of variables including stress range, rate of loading, load history, stress reversal, rest period, stress gradient, material properties, etc. The effects of these parameters on fatigue characteristics of concrete are addressed in this report. In general, endurance or fatigue limit of plain concrete was found to vary between 50 and 60% of its static strength. In compressive mode of loading, concrete containing a class C fly ash showed improved fatigue strength over either concrete contained class F fly ash or no fly ash. However, in flexural mode of loading, inclusion of fly ash in concrete exhibited little effect on the endurance limit of plain concrete.
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Rational design of concrete structures requires an accurate knowledge of concrete properties under anticipated loading conditions. A large volume of information is available on behavior of concrete under static loading conditions. However, relatively limited information is available on behavior of concrete subjected to dynamic loadings.

Structures that are subjected to repeated loads are susceptible to failure due to fatigue. Fatigue is a process of progressive permanent internal changes in the materials that occur under the actions of cyclic loadings. These changes can cause progressive growth of cracks present in the concrete system and eventual failure of structures when high levels of cyclic loads applied for short times or low levels of loads are applied for long times.

Many concrete structures such as highway pavements, highway bridges, railroad bridges, airport pavements and bridges, marine structure, etc. are subjected to dynamic loads. Fatigue strength data of concrete and other materials that are used in these structures for obtaining their safe, effective and economical design are needed. A low cycle fatigue is important for structures subjected to earthquake loads.
Although fatigue research began almost one hundred years ago, there is still lack of understanding concerning the nature of fracture mechanism in cementitious composite materials due to fatigue. This is partly due to complex nature of structure of such materials and their properties are influenced greatly by a large number of parameters. Fatigue behavior of concrete is also influenced by several parameters such as type of loadings, range of loading, rest period, material properties, environmental conditions, etc. The concrete properties are dependent upon the variables such as water-to-cement ratio, cement content, air content, curing technique, age, admixture content, etc.

A very limited information exist on concrete properties under various modes of cyclic loading, especially for plain concrete containing mineral admixtures. A number of investigations have been directed toward characterization of fatigue behavior of concrete and other materials under different loading conditions (1-98).

This research was undertaken to present the state-of-the-art information on fatigue behavior of plain concrete manufactured with or without fly ash. The report also provides extensive listing of references related to fatigue behavior of plain concrete, reinforced concrete, and prestressed concrete made with or without fly ash for reader interested in further in depth study of behavior of concrete subjected to fatigue loadings.
GENERAL

Fatigue in material occurs when they are subjected to rapidly fluctuating and cyclic stresses. In general, failure of materials occurs due to fatigue at stress levels much lower than yield strength of material for a static load.

Small flaws or discontinuity are present internally or on the surface of body. At these flaws stresses are very high due to stress concentrations affects. As a result, under the cyclic loadings, cracks can grow at these flaws due to plastic deformations even if applied normal stresses are lower than the elastic limit. The cracks can grow by a mechanism of reversed slip for a metal (50). When the crack length becomes large, the intact portion of a structure can not sustain the applied due to reduced stress resisting area. This results in a very rapid crack growth resulting in an abrupt failure of the material. The fatigue life of a material depends upon type and magnitude of the applied cyclic load.

BEHAVIOR OF MATERIALS UNDER CYCLIC LOADINGS

The mechanical response of a material is substantially altered by cyclic loadings. In the case of metals, it depends greatly upon hardness of materials and experimental conditions. Under cyclic loading conditions, a metal may either harden, soften, remain stable, or have mix behavior (soften or harden depending upon strain level) (86). During constant
strain cycling of a material, an increase in stress with time is called strain hardening and a decrease in stress is called a strain softening. These are related to the nature and stability of the dislocation substructure of a given metallic material (86).

In general, the dislocation density is low for soft materials. For such a material, the increase in the density resulting from cyclic plastic straining causes strain hardening. Whereas for a hard metal, the cyclic strain causes a rearrangement of dislocations. The resulting structure for the metal becomes soft as it offers low resistance to deformation (86).

A kinematically irreversible microscopic deformation is the precursor to fatigue in both ductile and brittle solids (98). It is now well established that the cyclic slip is not only cause of fatigue damage but it can occur due to microcracking, interfacial sliding or creep, etc. The irreversible deformation in brittle solids can occur due to various processes. These include (98): (1) frictional sliding of the microcracks that are nucleated at grain boundaries, and along the interfaces between the matrix and the filler, (2) the release of residual stresses may cause microcracking at the grain boundaries and the interfaces resulting in plastic deformation strain, etc.

Concrete is a complex hybrid composite material. During cyclic loading fracture to concrete can occur by fracture of the cement paste, fracture of aggregate, failure of bond between the cement paste aggregate or any combination of these mechanism.
Compared to metals, concrete is prone to have large number of flaws resulting from hydration, shrinkage and other causes. Mechanism of fatigue in concrete is not well established and numerous hypothesis related to crack initiation and propagation have been proposed by Neal and Kesler (16), Kesler (3), Raithby and Whiffin (25), and several others (75,76).

Mudock and Kesler (6) proposed that initiation of fatigue failure in concrete is due to progressive deterioration of the bond between the coarse aggregate and the matrix. This results in reduction in section of the specimen leading to its failure due to fracture of matrix. However, most researchers support that during cyclic loading, fatigue of concrete occurs because of the propagation of the micro cracks and macro cracks present in the material, especially in the interface region as well as in the matrix. Since the interface region is the weakest region, there is a very high probability that initiation of fatigue cracks occurs in this region. However, initiation of fatigue cracks can occur either in matrix or at the interfacial region would greatly depend of the size of flaws present.

Addition of fiber to concrete restrict crack formation and delays crack growth. Therefore, unstable cracks produced during loading is transformed into a slow and controlled growth. Also, crack path length is increased in presence of fibers. The overall tensile rupture strain of concrete is increased due to introduction of fiber. This depends greatly upon the elasto-plastic properties of the fiber and the effectiveness of the bond between the fibers and the concrete matrix. Due to improved ductility of the fiber reinforced concrete, their dynamic properties including fracture toughness and fatigue life are greatly
improved. To some extent, the presence of fine and coarse aggregates in the cement paste improves its toughness due to increased crack propagation path length.

FATIGUE LIFE PREDICTIONS DUE TO CONSTANT LOADINGS

Fatigue life of a component is composed of time required to initiate a crack and time required to propagate it. At low levels of cyclic strain, majority of the fatigue life (up to 90%) is made of crack initiation time. Whereas in the case of high strain cycles, most of the portion of fatigue life is composed of crack propagation time.

Paris et al. (10,11) describe the use of fracture mechanics in characterizing crack growth due to fatigue loadings. A schematic of crack growth rate curve for a material is shown in Figure 2-1. This curve has three distinct regions. In regions I and II, the curve is non-linear and becomes linear for the region II. Crack growth rate is nearly zero or too low to measure below the threshold stress intensity factor ($\Delta K_{th}$).

Linear elastic fracture mechanics (LEFM) concept is mostly used to model crack growth rate associated with Region II. Paris and Erduga (10) were probably first to develop the power law relationship for fatigue crack growth rate in Region II, as described below.

$$\frac{da}{dN} = C \Delta K^m$$
Where

\[
\frac{da}{dN} = \text{crack growth per cycle;}
\]

\[
\Delta K = K_{\text{max}} - K_{\text{min}} = \text{the stress intensity range;}
\]
\[ K_{\text{max}} = \text{the stress intensity factor corresponding to maximum stress (} f_{\text{max}} \text{) for a stress cycle;} \]

\[ K_{\text{min}} = \text{the stress intensity factor corresponding to minimum stress (} f_{\text{min}} \text{) for a stress cycle;} \]

\[ R = \frac{K_{\text{min}}}{K_{\text{max}}} = \frac{f_{\text{min}}}{f_{\text{max}}} \; ; \text{ and} \]

\[ c \text{ and } m = \text{material constants} \]

The crack growth life, in terms of cycles to failure, can be obtained from Eq. 2-1 as:

\[ N_f = \int_{a_i}^{a_f} \frac{da}{(c \Delta K^m)} \]

Where \( a_i \) is the initial crack length and \( a_f \) is the critical crack length. \( \Delta K \) can be determined using the relation for crack intensity factor of the following form.

\[ \Delta K = K_{\text{max}} - K_{\text{min}} \]

\[ = f(g) f_{\text{max}} \sqrt{\pi a} - f(g) f_{\text{max}} \sqrt{\pi a} \]

\[ = f(g) \sqrt{\pi a} (f_{\text{max}} - f_{\text{min}}) \]
Where \( f(g) \) is a correction factor that depends upon specimen and crack geometry, and "\( a \)" is a crack length.

Several other attempts have been made to establish models for either all or a part of the curve representing crack growth rate and the stress intensity range. Forman et al. (20) proposed a model for Regions II and III incorporating the effects of \( R \) as

\[
\frac{da}{dN} = \frac{C \Delta K^{m}}{K_{crit} - \Delta K}
\]

or

\[
\frac{da}{dN} = \frac{C \Delta K^{m-1}}{\left(\frac{K_{crit}}{K_{max}} - 1\right)}
\]

The above model (Eq. 2-5) predicts infinite crack growth rate when \( K_{max} \) approaches the critical value of crack intensity, \( K_{crit} \). Similar models have also been proposed by other researchers (91). However, these models fail to represent the entire range of the curve.

A number of models have been proposed to describe the entire crack growth curve (91). Such a model, as proposed by McEvily (80), is given by:
The above crack growth rate models are based on linear elastic fracture mechanics approach. Due to non-linear fracture behavior of concrete, the models based on non-linear fracture mechanics should provide better representation of the crack growth curve compared to the model based on the linear fracture mechanics theory. A non-linear fracture mechanics theory was applied by Dowling and Begley (79) to describe crack growth rate. Their model is of the form:

$$\frac{da}{dN} = C(\Delta K - \Delta K_{th})^2 \left(1 + \frac{\Delta K}{K_{crit} - K_{max}}\right)$$

Where $J$ is an integral to describe energy release rate in nonlinear materials.

All the models can be integrated to determine their fatigue life as shown above for the model in Eq. 2- .

Recently, attempts have been made to model crack growth in concrete due to cyclic loading using fracture mechanics approach. Zang et al. (75) measured elastic modulus of plain concrete as a function of number of fatigue load cycles. They found when $\Delta K$ was less than $\Delta K_{th}$, the elastic
modulus of concrete was constant with increasing load cycles. When ΔK was increased beyond Kth, macroscopic cracks did not appear until about 95% of the fatigue life. Their results show linear decrease in elastic modulus up to certain number of load cycles beyond which it became nonlinear. Baluch et al. (76) carried out test to test validity crack growth model proposed by Paris and Erdogan. Their results revealed that this law is applicable to plain concrete. However, they reported that the model proposed by Foreman et al. (20) fail to provide adequate representation of crack growth rate for plain concrete.

DAMAGE EVALUATIONS DUE TO VARIABLE AMPLITUDE LOADINGS

Most structures are subjected to variable amplitude loadings during service which are quite complex. Fatigue crack growth rate in constant amplitude loading differ substantially from the variable amplitude loading conditions. In the former case the incremental crack growth depends greatly on the present crack size and the applied load, whereas in the latter case the incremental crack growth is also dependent on the preceding cyclic loading history (91). This is known as load interaction or sequence effects. The load interaction effects influence the fatigue crack growth rate significantly which in turn affect fatigue lives. Several models, developed by a number of researchers, to represent crack growth under variable amplitude loading, are summarized by Bannantine et al. (86).

Numerous methods are available to measure cumulative fatigue damage resulting from variable amplitude loading. In this report, damage summation methods for initiation of fatigue damage is described. These are linear damage rule and nonlinear damage theories.
Palmgren (1) was the first to propose the linear damage rule and was further developed by Miner in 1945. It is called as Polmgren-Miner rule or Miner's rule. This rule relates the damage caused by n cycles of loading of a particular amplitude level to the endurance limit. This is given by:

\[ D_f = \frac{n_f}{N} \]

where \( D_f \) = fatigue damage at an applied stress level of \( f \); \( n_f \) = number of cycles applied at a stress level \( f \), and \( N \) is fatigue life corresponding to endurance limit.

The accumulated fatigue damage caused by varying repetitive loading is expressed as:

\[ D = \sum_{i=1}^{P} \frac{n_i}{N_i} \]

where \( P \) = number of variable stress levels applied.

The cumulative damage theory assumes that failure will occur when \( D \) becomes equal to one. Several investigators have used two-stage load histories, low and high to test validity of Miner's rule. This involves testing initially at a load for a certain number of cycles and then the stress level is changed to second level until failure occurs. If the first stage load is a low level, then the fatigue test is called a low-high test and
a test having a reverse order of this type of loading is called a high-low test. The values of D is found to vary substantially depending upon loading conditions. Most researchers have found the value of D, based on the Miner's rule, between 0.5 and 2.0; generally the high-low tests give values less than 1, and the low-high tests show values greater than 1 (91).

The linear damage theory assumes that the rate of damage accumulation is independent of the level of applied stress. This is untrue because material response is greatly influenced by the levels of applied load. Additionally, the linear damage rule ignores the effects of loading sequence. To overcome these shortcomings, non-linear damage theories have been proposed by many researchers. Such theories involve considerable of testing work in determining material constants and involve substantial computation effort. A general model for a non-linear damage theory can be expressed as (91):

\[ D = \left( \frac{n}{N} \right)^b \]

where the exponent b, is a function of applied stress. The value of b increases with stress level in the range of 0 - 1.

TERMS RELATED TO FATIGUE

The following are the most common terms used in fatigue analysis of materials.
Maximum Stress ($f_{\text{max}}$)

It is the highest value of stress in a stress cycle, tensile stress being considered positive and compressive stress negative.

Minimum Stress ($f_{\text{min}}$)

It is the lowest value of the stress in a stress cycle, tensile stress being considered positive and compressive stress negative.

Stress Range ($f_r$)

It is defined as a difference between the maximum and minimum stresses in a stress cycle, that is, $f_r = f_{\text{max}} - f_{\text{min}}$.

Mean Stress ($f_m$)

It is defined as an average value of the maximum and minimum stresses in a stress cycle, that is, $f_m = 1/2 (f_{\text{max}} + f_{\text{min}})$.

Stress Ratio ($R$)

This is defined as the ratio of minimum stress to maximum stress in a stress cycle, that is, $f_{\text{min}}/f_{\text{max}}$.

Fatigue Life ($N$)

It is defined as the number of cycles which could be withstood for a given experimental condition.

Fatigue Strength ($f$)

It is defined as the intensity of cyclic stress that can be withstood for a given number of cycles.
Endurance Limit or Fatigue Limit ($f_e$)

It is defined as the maximum cyclic stress that can be withstood without failure, meaning that fatigue life is infinite below this stress level.
Section 3

PREVIOUS STUDIES

GENERAL

Several researchers including Nordby (5), Murdock (15), Lloyd et al. (24), Kesler (29) and Ronthby (42), etc. presented information on early studies concerning fatigue behavior of concrete. The earliest work on fatigue of mortar specimen in compression was done by Considère in 1898 and concrete specimen by Van Ornum in 1903 (5). However, substantial amount of research work on fatigue behavior of concrete began after 1930. This report deals with previous investigations related to fatigue behavior of plain concrete made with or without fly ash.

PLAIN CONCRETE

A large number of parameters are known to influence fatigue properties of plain concrete. These include stress range, variation in loads, load history, rate of loading, rest periods, stress gradients, material properties, etc. The material properties are influenced by cement content, water-to-cement ratio, curing conditions, amount of entrained air, specimen size, aggregate type and quality, moisture condition, age of concrete, etc. The effects of some of these parameters on fatigue behavior of concrete is presented in the following sections.

Stress Range

The effect of varying load levels on fatigue is of special importance because this condition is more representative of the actual conditions.
to which a structural component will be subjected. Several studies indicated that the range of stress influences the fatigue strength (6,19). In general, higher fatigue strength is obtained when the range of stress is reduced.

Murdock and Kesler (6) studied the effect the range of stress on flexural fatigue life of concrete. All specimens (6 in. x 6 in. x 64 in.) were simply supported on a 60-in span and subjected to repeated loads of varying range and magnitudes using third point loading systems. Four series of tests were carried out with the stress ratio, R of minimum applied stress to maximum applied stress varying from 0.13 to 0.75. Their test data revealed that the fatigue strength, at 10 million cycles increased from 56 percent of the modulus of rupture at R = 0.13 up to 85 percent of the modulus of rupture at R = 0.75 (Figure 3-1).

Hilsdorft and Kesler (19) evaluated the influence of variable loading on the flexural fatigue behavior of plain concrete. Test specimens (6 in. x 6 in. in cross sections) were loaded at a rate of 450 cycles per min. with a span of 60 in. A concrete mix proportioned to have an average compressive strength of 5000 psi at 28 days was utilized for this work. Test data are presented in Figure 3-2. The results presented in Figure 3-2 exhibit linear decrease in fatigue strength with increasing number of loading cycles between $10^2$ and $10^7$ cycles of concrete. This study indicated that concrete does not exhibit an endurance limit up to 10 million cycles. The results further show a decrease of the range between maximum and minimum load results in increased fatigue strength for a given number of cycles (Figure 3-2).
Awad (31) performed an investigation to evaluate the effect of maximum stress and stress range of plain concrete prisms subjected to high repeated and sustained loads. Compressive loads were applied concentrically to all specimens (4 in. x 4 in. x 12 in.). Four levels of maximum stress (95, 90, 85, and 80 percent of the initial static strength) were used. The stress range, R varied between zero and the maximum stress. The cyclic loads were applied at a constant stress rate of 6000 psi/min. for all the tests in this work. Their test results are presented in Figures 3-3 and 3-4.

Figure 3-3 shows that decrease in stress range, at an constant maximum stress, from its maximum value to 0.50, results in a considerably higher increase in the cycles to failure when compared to a decrease from 0.50 to 0.05, particularly at high values of f\(_{\text{max}}\). However, for higher maximum stress levels, particularly f\(_{\text{max}}\) = 0.95, and low stress ranges, R less than 0.50, the increase in failure cycles is low (Figure 3-4). Based on the analysis of test data, Awad (31) reported that when concrete is subjected to high repeated stresses, a decrease of maximum stress level and/or stress range results in an increase of the number of cycles to failure.

**Rate of Loading**

The influence of the frequency of loading has been investigated by several researchers (3, 9, 31, 34, 35, 37, 38). Since the static strength of concrete depends significantly on the rate of loading (25), it is anticipated that fatigue performance would also be effected by this parameter.

However, in general, variations of the loading frequency in the range
of 70–900 cycles per minute have insignificant effects on fatigue strength of concrete if the maximum stress level remains less than about 75% of the static strength \((3,84)\). However, for higher stress levels, fatigue strength decreases considerably with decreasing frequency of loading \((31,34,37)\). Under such conditions, creep effects become more dominant, probably leading to a substantial reduction in fatigue strength with decreasing rate of loading.

In 1950, Kesler (3) evaluated the effect of speed of testing on the flexural fatigue life of plain concrete. Test specimens used were 64 inches long, supported on a span of 60 inches, and loaded at one-third points. Two different strength levels (3600 psi, 4600 psi) of concrete were tested at rates of 70, 230, and 440 cycles per minute. Their results indicated negligible effect of rate of loading in the range of 70–440 cycles per minute.

Awad (31) studied the effect of rate of loading on the response of concrete to both static and high repeated loads. A total of 45 prisms (4 in. x 4 in. x 12 in.) were tested. The repeated loads were applied at rates of 600, 6000, and 60,000 psi/min. Various stress ranges (0.10, 0.50, or 0.90 of the static ultimate strength) were used. The test results reveal that for a constant stress range, varying the stress rate from 600 psi/min to 60,000 psi/min. increased the average cycles to failure by more than one order of magnitude.

Sparks and Menzies (34) determined the effect of the rate of application of fluctuating loads upon the fatigue strength of plain concretes in compression. Concrete rectangular prisms (102 x 102 x 203 mm.) made with
gravel, limestone or Lytag aggregate were tested. In order to maintain the loading and unloading rates constant, a triangular wave-form was employed in the fatigue tests. The frequency of loading applied to the prisms varied from prism to prism, depending upon the level of the maximum load in the cycle. The frequencies were adjusted to obtain the required rates of loading and unloading of either 0.5 or 50 MPa/s. Test results indicate that typically a hundredfold increase is the rate of loading produces a tenfold improvement in the mean fatigue life for stresses above about 75% of the static compressive strength (Figures 3-5 through 3-7).

This means that accelerated fatigue tests on concrete structures may give an overestimate of their true fatigue life under loading rates which may occur in service, particularly for high cyclic stresses.

Galloway and Raithby (35) evaluated the effects of rate of loading and frequency on fatigue performance of concrete. Two different types of plain concrete, one having an uncrushed flint gravel aggregate (PQ1) and the other a crushed limestone (PQ2), were made. From each batch of concrete, six 508 mm x 102 mm x 102 mm beams and five 152 mm x 102 mm diameter control cylinders were manufactured. Concrete (PQ1), was tested in both saturated and surface-dry moisture conditions at loading frequencies of 4 Hz and 20 Hz, and concrete (PQ2) was tested only in saturated moisture condition at 20 Hz. All fatigue tests were conducted under constant amplitude sinusoidal loading in which the minimum load was kept zero. The results were presented in Tables 3-1 and 3-2 and Figure 3-8. The test data revealed that frequency of loading had insignificant effect on fatigue performance over the range 4 Hz to 20 Hz.

Raithby and Galloway (38) conducted a fatigue study on the effect of rate
of loading using a medium-strength concrete (PQ1) made with an uncrushed flint gravel aggregate. Most of the tests were carried out at a frequency of 20 Hz but some tests were run at 4 Hz on both saturated and surface-dry beams (102 x 102 x 510 mm). The test data showed insignificant difference in fatigue strength determined in the range of 4 to 20 Hz loading cycle (Figure 3-9).

Sparks (52) reported a study on the influence of rate of compressive loading and material variability on the fatigue characteristics of plain concrete. Test specimens were manufactured with a typical normal weight aggregate, gravel, and a manufactured lightweight aggregate, Lytag, were tested at one of two constant rates of stressing and unstressing, 0.5 MPa/s and 50 MPa/s. Due to two different rates of loadings, two curves were observed for each concrete system; the strength increased with the rate of loading. However, when the fatigue data were related to static strength at a standard stressing rate, the results could be represented by a single response curve for each concrete. (Figures 3-10 and 3-11). From the results obtained it was found that for most of the life of the specimen, the rate of strain increase per cycle of load was constant. A strong relationship existed between this strain rate and the number of cycles to failure.

Holmen (54) investigated the frequency effects on the fatigue behavior of plain concrete. The main part of the investigation was performed with loading speed of 300 cycles per minute (5 Hz), while a few tests were performed with 60 and 600 cycles per minute. Test results showed that a reduction in the speed of testing seems to shorten the fatigue life, especially at high stress levels. This is in agreement with other
investigations performed by Awad and Hilsdorf \(^{(37)}\).

**Load History**

Majority of studies on the fatigue characteristics of concrete have been directed toward determining the influence of constant amplitude loading. However, in actual structures, such as concrete bridges, offshore structures, and concrete pavements, the applied stress cycles vary substantially in magnitude, number and order \(^{(62)}\). Not much work has been published on the behavior of concrete under variable amplitude loading \(^{(42)}\).

In order to handle variable amplitude loadings, mostly Miner hypothesis has been utilized \(^{(84)}\). The Miner hypothesis assumes that damage accumulates linearly with the number of cycles applied at a particular load level. According to this rule, failure occurs if \(\sum (n_i/N_i) = 1\), where \(n_i\) is the number of cycles applied at a particular stress condition, and \(N_i\) is the number of cycles which will cause fatigue failure at that same condition \(^{(84)}\).

Hilsdorf and Kesler \(^{(19)}\) were probably the first to study the influence of variable stress amplitude levels on the fatigue behavior of plain concrete. The primary objective of their study was to study the validity of the Miner hypothesis in flexural modes of cyclic loading. The loading programs composed of blocks with two different stress levels. Their results showed that when the lower stress level was applied first, the Miner hypothesis was unsafe, whereas when the higher stress level was applied first, the Miner hypothesis was conservative.
Based on tests limited in scope, design, curves as shown in Figure 3-12, have been developed so that when the Miner hypothesis is applied to obtain better results at various levels of probability of failures (19). Test results from multi-stage block compression loadings have shown both conservative and unsafe prediction of the Miner hypothesis (62).

Recent studies (54,91) with random loadings, which simulate the actual loading conditions more closely, have substantiated that variable amplitude is more damaging than predicted by the Miner hypothesis. This is primarily due to the fact that loading sequence has considerable effect on the damage which is ignored in the Miner hypothesis. However, other investigations showed that the Miner hypothesis is applicable to the estimation of fatigue life of concrete subjected to random loadings (58,63,74).

Holmen (54) carried out an investigation to study the effect of various load histories on the fatigue behavior of plain concrete in compression.

In this investigation, two different loading systems were followed. The first system consisted of two-stage constant amplitude loading, while the second was random loading. The two-stage loading was used to verify the Palmgren-Miner hypothesis. The results showed that the fatigue life of test specimen was greatly influenced by the order of application of the two-stage loadings. This means that significant sequence-effect exists under the two-stage loading which the Polmgren-Miner hypothesis ignores. Several researchers have also shown similar results (37,50).

In the case of random loading, 30 specimens were tested under different loading histograms and frequencies. Two main different loading
histograms were used: one with constant minimum stress level \((f_{\text{min}} = 0.05)\) and the other with constant mean stress level \((f_{\text{m}} = 0.50)\). A computer program was used to apply three different loading models. Model 1 was composed of constant mean stress level \((f_{\text{m}})\) and the range of peaks and troughs was divided into 31 intervals. Model 2 loading was made up of all troughs with the same level \((f_{\text{min}} = \text{constant})\), but range of possible peaks contained 15 levels. Model 3 had all troughs with the same stress level \((f_{\text{min}} = \text{constant})\), but the range of possible peaks was increased to 30. In all these models, amplitude of loadings were (large or small) modified as given in Table 3-3. All these tests were performed with a loading speed of 300 cycles per minute (5 Hz). Test data are presented in Table 3-3. His test results show that: (1) the variable amplitude loadings cause more damages than predicted by the Palmgren-Miner hypothesis which is due to the loading sequence effects, (2) loading histograms with lower minimum stress levels caused stronger sequence effects and will, therefore, be more damaging, and, (3) the presence of small amplitudes in a loading histogram reduced the sequence effects. Based on the test results, Holmen (54) suggested a modified version of the Palmgren-Miner hypothesis as:

\[
\frac{1}{w} \sum_{i=1}^{n_i} \frac{n_i}{N_i} = 1 \quad \sum_{i=1}^{n_i} \frac{n_i}{N_i} = w
\]

where \(w\) is a function of loading parameters.
The effects of stress reversal on the fatigue life of plain concrete have been studied to a very limited extent. The stress reversal produces shorter fatigue life of concrete compared to concrete subjected to stress cycles having positive stress ratio.

Murdock and Kesler (6) carried out fatigue tests by using various combinations of axial and flexural loads in order to vary the extreme fiber stress from tension to compression, and partial or complete reversals. A modified Goodman diagram (Figure 3-13) was developed based on their test results and data reported in the literature. The data suggested that stress reversal had a very small influence on the fatigue strength.

In 1979, the Swedish Code BBK 70 (47) considered a reduction of design stress due to fatigue caused by stress reversals between tension and compression. Tepfers (55), performed tests to investigate the fatigue behavior of plain concrete subjected to stress reversals using cube prism specimens. His results revealed that stresses alternating between tension and compression cause a slight reduction in fatigue strength of concrete. However, the author indicated that the reduction obtained may be due to difficulties in loading the specimens precisely on the tensile side of the load pulses.

Recently, Zhang et al. (85) studied the effect of stress reversal on the fatigue life of plain concrete through flexural fatigue tests on plain concrete beams. A series of seventy (500 x 100 x 100 mm) beams were tested under third-point bending loads with an effective span of 450 mm.
The loading frequencies were 1 Hz for low fatigue life \((N < 10^3)\), 5 Hz for middle fatigue life \((10^3 \leq N \leq 10^5)\), and 20 Hz for high fatigue life \((N > 10^5)\). Four different stress ratios, \(R = -0.2, -0.5, -0.8, \) and \(-1\), and nine different stress levels, \(f_{\text{max}}/f_r = 0.50\) to 0.90, were examined. The test results indicated that the stress ratio significantly influence the fatigue properties of concrete. The results show that stress reversal decreases the fatigue life of concrete, but the reversal effects become smaller when \(R \geq 0\). A new fatigue equation containing the effect of stress reversal on the fatigue properties of concrete was proposed as follows:

\[
f_{\text{max}}/f_c = C_f \left[ 1 - (1 - R')\beta \log N \right]
\]  

(3-1)

where \(f_{\text{max}}\) is maximum cyclic stress, \(f_c\) is the static strength, \(N\) is fatigue life, \(\beta\) is material constant, and \(C_f\) is loading frequency coefficient defined by:

\[
C_f = ab^{-\log f_w} + c
\]

(3-2)

where \(f_w\) is loading frequency in Hz, and \(a, b\) and \(c\) are material constants, \(R\) is a new stress ratio defined as follows:

\[
R' = \begin{cases} 
R & R \geq 0 \\
R(f_{\text{max}}/f_{\text{min}}) & R < 0
\end{cases}
\]

where \(f_{\text{max}}\) and \(f_{\text{min}}\) are maximum and minimum cyclic stress, respectively.
Previous Stress History

Mostly the static strength of concrete is not adversely affected by the previous stress history of the test specimens given that the applied stresses are less than fatigue strength at $10^7$ cycles \(25\). In fact test results have exhibited that a specimen exposed to cyclic loading for a given cycle ratio exhibits an increased strength when tested statically.

Bennett and Raju \(30\) observed 11% increase in static strength of high strength concrete specimens which were previously subjected to several million applications of cyclic loads between 0.5 and 0.7 of the static ultimate strength. It has also been found that beams specimens subjected to a similar stress history resisted increased number of load applications when tested later at a higher stress level compared to control specimens which were not loaded previously \(24\).

A number of possible explanations of the observed strengthening effects have been reported as given below \(30\).

1. The strength increase may be related to the temperature rise observed during cyclic loadings. This may result in a slight increase in the relative to controls. Additionally, an increase in the loss of capillary moisture due to the heating can also result in increased strength.

2. Similar to that observed for the sustained compressive loads, increased strength can be attributed to the loss of gel moisture, that occurs due to the temperature rise.

3. Cyclic loads can release the residual stresses which may lead to increased strength.

4. Cyclic loads may increase strength because of the strain hardening effects.

Rest Periods

Studies have shown that rest periods and sustained loading between the repeated load cycles appear to have a beneficial effect on the fatigue
strength of concrete $(6, 19, 66, 38)$. This effect is only true when there are no stress reversals and if the sustained stress level is below 75 percent of the static strength. The increase in strength is attributed to the relaxation of concrete $(95)$.

Murdock and Kesler $(6)$ tested specimens under fatigue loading with load periods interrupted by intermittent rest periods (five-minute periods of rest were inserted between ten-minute periods of loading). Their test results indicated that the rest periods were beneficial in improving the fatigue strength determined at ten million repetitions of load (Figure 3-14).

Hilsdorf and Kesler $(19)$ evaluated the effect of rest periods by subjecting test specimens to relatively low levels of sustained stress with different range of duration of 1, 5, 10, 20, and 27 minutes. The results show that rest periods of up to 5 minutes increased the fatigue strength but the periods longer than 5 minutes had no further effect (Figure 3-15).

Raithby and Galloway $(38)$ found reduction in fatigue life of concrete at a particular stress level when a rest period of constant duration was imposed after each loading cycle with rest of up to 2 seconds. However, in the case of rolled asphalt where it has been shown that short rest periods (1 second duration) between successive loading cycles have a significant effect on fatigue performance $(38)$.

**Stress Gradient**

Ople and Hulsbos $(17)$ carried out an investigation to see the effect of stress gradient on the fatigue strength of concrete in compression. Their
results on 4 x 6 x 12 in. (102 x 152 x 305 mm) concrete prisms under repeated compressive stresses and three different stress gradients are shown in Figure 3-16. Concrete prisms with compressive strength of about 6000 psi (41.4 MPa) were subjected to a loading rate of 500 cpm at ages varying between 47 and 77 days. To simulate the compression zone of a beam, load was applied eccentrically in the fatigue tests of concrete prisms (17).

The test data indicated that the fatigue strength of eccentric specimens is 15 to 18 percent higher than that for uniformly stressed specimens for a fatigue life of 40,000 to 1,000,000 cycles (Figure 3-16). Based on the test results obtained, the authors recommended that the fatigue strength of uniformly stressed specimens be used as a lower limit of fatigue life of flexural members in compression, such as prestressed members.

**Age at Loading**

As expected, age and curing have a decisive effect on the fatigue strength. Concrete inadequately cured is less resistant to fatigue than a well-cured concrete at a given age (5). In general, test data showed increase in fatigue strength of concrete with age in young specimens up to about 3 months after casting, and beyond this the increase became insignificant (5).

Kesler and Siess (4) stated that specimens for fatigue testing should be at least three months old before testing, in order to eliminate the influence of continued hydration during the fatigue test.

Linger and Gillespie (18) are probably the first to investigate systematically the effects of concrete age on fatigue behavior in compression. They found that fatigue strength increased with age.
linearly, especially during the first three months. They did not determine the static ultimate strength at the time the fatigue testing but used the 28-day strength as the basis for comparison. The results revealed an increase in fatigue strength for $10^6$ of cycles from 0.64 at 40 days to 0.82 at 84 days.

Awad (31) evaluated the effect of concrete age under cyclic loading at an age of 7, 28 and 90 days. Concrete with a control cylinder strength of 4000 psi after 28 days was used. Figure 3-17 show the effect of age on the fatigue life for maximum stress levels, $f_{\text{max}} = 0.95$, 0.90, and 0.85 and stress ranges $R = 0.50$ and $R = f_{\text{max}}$.

Awad (31) concluded that the age of concrete has little effect on the number of cycles to failure for stress levels greater than 0.90. At stress levels of 0.95 and 0.90 of the static ultimate strength, the time to failure decreases with decreasing age of concrete. For lower repeated stresses, the load dependent damage can be offset partially by a gain in strength due to the continued hydration during loading.

Raithby and Galloway (38) studied the effect of age on the fatigue performance of three types of plain concrete: Type PQ1 were made on a medium-strength concrete having an uncrushed flint gravel aggregates; Type PQ2 is a pavement quality concrete having the same workability and nominal 28-day indirect tensile strength as PQ1 but having crushed limestone coarse aggregate; and Type LC1 ia a lean concrete made with flint gravel aggregate similar to that used in PQ1. The fatigue tests were performed by testing specimens of each type at particular stress levels for various curing times ranging from 28 days to 3 years. The
results indicated a substantial increase in fatigue endurance with age, the actual gain being dependent on the type of concrete and on the stress level.

Galloway et al. (44) conducted an experimental investigations to evaluate the effects of age on flexural fatigue strength of concrete. Experiments were conducted on three types of concrete as described previously (35). Six beam specimens of (508 x 102 x 102 mm) beams were cast from each batch of concrete. Specimens from Type PQ1 were cured under water for time periods within 28 days to 5 years for fatigue tests. Specimens from Types PQ2 and LC1 were cured under water between 3 months to 2 years. Test specimens were loaded at the middle third-points with a span of 406 mm at a loading frequency of 20 Hz, with a minimum load of approximately zero. The maximum load was varied to establish fatigue endurance curves for each of the three types of concrete at an age of 26 weeks, and to determine endurance at particular maximum stress levels at different ages.

The results of the fatigue tests were presented in Table 3-4 and Figure 3-18.

Based on the results obtained, the authors concluded that fatigue endurance at particular stress levels increased significantly with age up to 5 years. The results for all three concretes could be represented by a single fatigue endurance curve if the fatigue strength is expressed as a proportion of the appropriate flexural strength at the same age (Figure 3-18). The authors, based on test data, reported that the fatigue performance at any age may be predicted with acceptable accuracy from the results of static flexural strength tests at the same age.
Moisture Conditions

Relatively, limited number of research work has been done to evaluate the effect of moisture condition on fatigue strength of concrete. Variations in moisture condition may result in moisture gradients within the test specimens, resulting in relatively high initial surface strains that can cause local shrinkage cracks (62).

Galloway et al. (44) investigated the effects of changes in moisture conditions on flexural fatigue performance of concrete at the time of testing. The moisture content investigation was confined to a concrete mix (PQ1) having uncrushed flint aggregate. All concrete specimens were cured under water for 26 weeks. These specimens were then conditioned in four different ways: (1) Saturated throughout the duration of the test; (2) Surface-dry (the beams were allowed to dry for one week in the lab atmosphere before being tested); (3) Oven-dried at 105°C for one week before being tested; (4) Oven-dried and then soaked in water for three weeks before being tested in a wet condition. All tests were conducted at 20 Hz maintaining constant load amplitude, with a minimum load of nominally zero. Test results are given in Table 3-5. The comparative endurance curves for each of the different moisture conditions are presented in Figure 3-19. The authors reported that flexural fatigue performance generally followed the same trend as observed with the static flexural strength of concrete. Of the four moist treatments, the maximum flexural and fatigue strengths were observed with oven-dried specimens and the minimum with specimens that were air-dried for seven days (Figure 3-19).

Curing Conditions
The effects of various concrete curing techniques such as immersion in water, curing in high humidity air (fog room) or curing in air at normal room temperature and humidity on fatigue strength have been investigated. Tests have shown as significant effect of the moisture condition at the time of testing on strength, stiffness and fatigue performance of small beams specimen cured by immersion in water for 26 weeks (43). Galloway et al. (43) also conducted experiments to determine the effect of curing methods on such properties. Test specimens (102 mm x 102 mm x 508 mm beams) were cured for 26 weeks at a controlled temperature of °F (20°C ± 1°C). Test specimens were cured by each of the following methods: (1) immersed in water for 26 weeks; (2) 13 weeks in water and 13 weeks in air at 65% relative humidity (RH); (3) 4 weeks in water and 22 weeks in air at 65% RH; (4) 1 week in water and 25 weeks in air at 65% RH; (5) 26 weeks in air at 65% RH; (6) 26 weeks in air at variable humidity; (7) 26 weeks in a fog room at 95% RH; (8) sealed in paraffin wax and kept at 65% RH; (9) sealed in a polyethylene bag and kept at 65% RH; and, (10) sealed with a coating of sodium silicate and kept at 65% RH. Test results of the fatigue tests are summarized in Table 3-6 and Figure 3-20.

The flexural fatigue strength data of the various groups followed a similar trend as that observed for flexural strength. The maximum flexural and fatigue strengths were obtained when the concrete was first immersed in water for one to four weeks, followed by air-drying in the laboratory. Immersion for 26 weeks or for 13 weeks followed by air drying for 13 weeks showed slightly lower values, and specimens which were air cured for the 26 weeks were the weakest. However, when fatigue strength was
expressed as a proportion of the flexural strength, all data points could be represented by a single S-N curve (Figure 3-20). This means that it is possible to predict approximately the effect of curing conditions on fatigue of concrete from the corresponding values of static modulus of rupture.

**Air Entrainment**

The influence of air content on most concrete properties, such as compressive strength, workability, durability, and creep, are well known. However, limited amount of work has been done concerning the effect of air content on the fatigue strength of plain concrete.

Antrim and McLaughlin (8) carried out axial compression fatigue tests on air entrained as well as non-air entrained concretes. This study showed that fatigue behavior of non-air entrained plain concrete and air entrained plain concrete in compression were essentially the same. However, air entrained concrete exhibited longer fatigue life at low stress ratios and shorter fatigue life at higher stress levels (Figure 3-21).

An extensive experimental investigation was performed at Iowa State University to evaluate the flexural fatigue behavior of air-entrained concrete. In the first phase of this study, Lee et al. (40) tested concrete beams at five levels of air content (2.8, 3.5, 6.4, 10.2, and 11.3%) for fatigue strength determinations. All other variables (e.g., type of cement, water-to-cement ratio, and type of coarse and fine aggregates, etc.) were maintained constant. In the second phase of the study, Klaiber et al. (41) evaluated the effects of air content, water-to-cement ratio, and aggregate type on the flexural fatigue strength of plain concrete.
A total of fifteen series of concrete were made in the second phase of this study (Table 3-7). For both the phases, all fatigue specimens (6 in. x 6 in. x 36 in. beams) were subjected to flexural one-third point loading. The bottom fiber stress was varied from a minimum to a maximum stress. The maximum stress level used were 60, 70, 80, or 90% of the modulus of rupture, and the minimum was kept essentially zero. Test results are presented in Figures 3-22 and 3-23.

Some typical test results are presented in Figures 3-37 and 3-40. Their results showed that the fatigue strength decreases as the air content increases regardless of the aggregate or water-to-cement ratio. Figure 3-23 presents the 95% confidence limits for concretes with 11.3% and 2.8% air content.

The authors concluded that the fatigue behavior of plain concrete in flexure is significantly affected by the air content of the concrete. They further reported that as the air content increases, the failure of concrete subjected to fatigue occurs increasingly at the aggregate-cement paste boundary.

Water-to-Cement Ratio
Fatigue strength of concrete decreases slightly with leaner mixes and increase in the water-to-cement ratio (5).

Klaiber et al. (41) reported the results of their study on the flexural fatigue behavior of concrete as a function of water-to-cement ratio.

Concrete specimens were made with varying water-to-cement ratio (low,
normal, and high), air content, and types of aggregate. Series designations of various material combinations are given in Table 3-7. A polymer-type water reducing agent was used with a water-to-cement ratio of 0.32 to obtain a workable concrete mix. Their test results are presented in Figures 3-24 through 3-31. The results showed no consistent trend concerning the effect of varying water-to-cement ratio on fatigue behavior of concrete.

For low air content, the low water-to-cement ratio (0.32, Figure 3-24) produces a concrete with a higher fatigue strength compared to the medium and high water-to-cement ratio (0.41, Figure 3-30, and 0.60, Figure 3-28). For air contents around 6%, the low water-to-cement ratio (0.32, Figure 3-25) concrete exhibited a lower fatigue strength than the medium and high water-to-cement ratio concretes (0.41, Figure 3-31; 0.43, Figure 3-27; and 0.60, Figure 3-29). For high air contents around 10%, the lower water-to-cement ratio concrete (0.32, Figure 3-26) have a much lower fatigue strength relative to the concrete made with the water-to-cement ratio of 0.41 (Figure 3-31). The concretes made with water-to-cement ratios of 0.41, 0.43, and 0.60 indicated similar fatigue strength.

**Type and Quality of Aggregate, and Concrete Strength**

Gary et al. (12) investigated fatigue behavior of concrete made with two different lightweight aggregate, one proportioned for a high strength (f'c = 6000 psi) and the other for a low strength (f'c = 3800 psi). Cylindrical specimens (3 in. x 6 in.) of approximately the same age were tested at stress levels of 40, 50, 60, 70, and 80 percent of the ultimate static compressive strength. Cyclic compressive tests were carried out at varying loading rates of 1000 to 500 cycles per min.
Test data indicated similar fatigue strength for low as well as high strength concrete when expressed as percentage of their respective static ultimate strength (Figure 3-32). While comparing the results obtained for normal weight concrete obtained from an earlier study and data observed for lightweight concrete in their study, the authors concluded that the fatigue behavior of these concretes is essentially the same.

Bennett and Muir (22) investigated the influence of the static strength and maximum size of coarse aggregate on concrete fatigue strength. Two types of high-strength concrete (6000 and 8500 psi), each made with two sizes of coarse aggregate (3/4 in. and 3/8 in. in maximum size). The results, obtained from extrapolation, showed compression fatigue strength of about 55 percent of static ultimate at $10^7$ cycles (Figure 3-33). The fatigue strength, after one million repetitions, ranged from 66 to 71% of the static strength. The fatigue strength of the stronger mix was slightly lower than that indicated by the weaker mix (Table 3-8).

Raithby and Galloway (38) evaluated the fracture characteristics of concrete using different coarse aggregates. The appearance of failure surface in fatigue was similar to that observed in modulus of rupture and indirect tensile tests for the specimens made with flint gravel aggregate. Cracks primarily progressed around the aggregate particles and considerable loss in adhesion between the mortar and aggregate occurred, and only very few of the stones fractured. However, concrete made with limestone aggregate showed no evidence of bond failure and failure was primarily due to tensile stress. The flexural and fatigue strength of the limestone concrete was found to be significantly higher relative to
the flint gravel concrete.

Sparks and Menzies (34) reported data on compression fatigue tests of lightweight concrete made from sintered pulverized fuel ash (pfa). Their results showed slightly inferior fatigue performance for this lightweight aggregate concrete when compared with a gravel concrete and a limestone concrete.

Sparks (52) further confirmed the earlier investigation (34) by using two different types of coarse aggregate (gravel and Lytag). Based on the test result derived, he concluded that a reasonable estimate for fatigue limit of gravel concrete is 55% of the ultimate static corresponding to $10^7$ cycles of load, but for Lytag concrete it is a serious overestimate.

Tepfer and Kutti (45) determined the fatigue strength of plain, ordinary, and lightweight concrete under the action of compressive stresses. Lightweight concrete of two densities (1500 to 1800 kg/m$^3$) was tested and compared with ordinary concrete (2250 kg/m$^3$ density). The test results revealed no significant difference between performance of the two concretes. Based on the experimental results obtained in this work as well as data from literature, the authors reported that both types of concrete have the same susceptibility to fatigue.

Klaiber et al. (41) studied the effect of aggregate types on the fatigue behavior of plain concrete in flexure. In their study, two types of coarse aggregates (gravel and crushed limestone) and two types of fine aggregates (Hallett sand and Bellevue sand) were used. Series designation of various
material combination are given in Table 3-7. Test results confirmed that the fatigue properties of plain concrete in flexure is substantially influenced by the coarse aggregate type used in the concrete. The concrete made with gravel exhibited a higher fatigue strength than the concrete made with limestone. However, at lower stress levels, this difference became insignificant. Their test result further revealed that the fatigue behavior of plain concrete in flexure may be affected by the type of fine aggregate used. A slight increase in fatigue strength of concrete was observed when a higher quality fine aggregate is used.

**Superplasticizer**

Numerous studies have been conducted on the physical properties of superplasticized concrete, but very little research has been published on the fatigue properties of superplasticized concrete.

Whiting (48) was probably the first to study the fatigue properties of superplasticized concrete. But the results of the study were not conclusive due to the limited scope and scatter of data obtained.

Lee et al. (65) carried out an investigation to determine the fatigue properties of concretes containing superplasticizers. A total of eight mixes and 120 concrete specimens (3 in. x 6 in. cylinder) at three levels of water-to-cement ratio (0.4, 0.5, and 0.6), and two levels of cement content (normal and high cement contents), with and without superplasticizers, were subjected to compressive fatigue testing. The load applied was varied from a minimum of 100 lb (445 N) to a predetermined maximum load corresponding to 80, 65, and 50 percent of the ultimate compressive strength. Tests were conducted at a frequency of 4 Hz using
MTS fatigue testing machine. Test data revealed that the fatigue behavior of plain concrete (W/C = 0.4, 0.5, and 0.6) in compression was not significantly changed by adding superplasticizers. The results further showed that high cement content did not significantly affect the fatigue strength.
FLY ASH CONCRETE

Fly ash has been used in concrete as partial replacement of cement because of economic considerations and its beneficial effect on the properties of concrete. The inclusion of fly ash in concrete effects all aspects of concrete properties. Substantial amount of research have been done concerning the physical properties of concrete containing fly ash. It is now well documented that fly ash causes improvement in workability, cohesiveness, ultimate strength and durability. However, relatively small amount of data is available on the fatigue behavior of concrete incorporating fly ash. The fatigue properties of lime-fly-ash-aggregate mixtures as pavements bases have been determined (13,14). Recently, some data on the fatigue properties of portland cement concrete in which cement is partially replaced by fly ash has been reported.

Ghosh et al. (59) studied the fatigue strength on lean cement-fly-ash concrete as a construction material. Both plain lean cement concrete and lean cement-fly-ash concrete were considered in this work. The mix proportions were 1 cement : 4 sand : 8 coarse aggregate for plain concrete, and 1 cement : 3.5 sand : 3.5 n fly ash : 14 coarse aggregate for lean cement-fly-ash concrete (n is ratio of specific gravity of fly ash and sand). At 28 days, specimens (7.5 x 10 x 50 cm) were tested for flexural fatigue at a loading frequency of 74 cycles per minute. The stress was applied through third-point loading using a pre-calibrated loading plate for accurate strain measurement. The cyclic loading consisted of a constant lower limit of zero and the upper limit in the range of 50 - 90% of the flexural strength. Test result indicated that at 75% maximum stress level, the number of repetitions to failure was $2 \times 10^3$ and $2 \times 10^4$ for plain and cement-fly ash, respectively. Specimens showed fatigue
limit of 50% of the flexural strength or more. However, the fatigue behavior of both types of concrete was found to be similar under repeated loading conditions within the tested range.

Burcharth (67) has described the performance of unreinforced and reinforced fly ash concrete under simulated loadings for concrete armour units.

Tse et al. (73) investigated fatigue behavior of concrete incorporating large quantities of fly ash. They used four levels of cement replacements (0, 25, 50, and 75%) by Class C and Class F fly ashes. The water-to-cementitious ratio varied between 0.3 to 0.37 for Class C fly ash mixes and 0.26 to 0.45 for Class F fly ash mixes. More than 350 concrete specimens were cured for 28 days and subjected to compressive fatigue loadings. The stress was varied from essentially zero to a predetermined maximum stress as percentage of the compressive strength (between 55% to 95%). A constant frequency of 4 Hz was used throughout the tests. The fatigue strength of concretes are given in Figures 3-34 and 3-35. The results exhibited that the fatigue strength of concrete depended greatly upon both type of fly ash and levels of cement replacement by fly ash. Based on the result derived, the authors indicated that concrete with equivalent or higher compressive and fatigue strength could be obtained with cement replacement of 25% by weight of low-calcium fly ash or 50% by weight of high-calcium fly ash.

Ramakrishnan et al. (92) evaluated flexural fatigue strength and endurance limit for air-entrained superplasticized high-volume class F fly ash concrete and plain concrete. Concrete mixture was proportioned to 58%
cement replacement with a low-calcium fly ash. The water-to-cementitious ratio was kept at about 0.32 and the desired workability was achieved through the use of a naphthalene base superplasticizer. A total of 40 beams, 20 beams of 75 x 100 x 400 mm (3 x 4 x 16 in) for each mix were made and were subjected to third-point loading with a span of 12 inches to determine the flexural fatigue strength. Each beam was subjected to non-reversed fluctuating loads at loading frequency of 20 Hz. (The lower limit was kept constant). The constant lower limit was taken as 10% of the flexural static strength, and the upper limit varied from about 90% of the static strength down to the fatigue limit. Test results are shown in Tables 3-9 through 3-12 and Figures 3-36 and 3-37. The fatigue test was run between lower load limit (10%).

The results revealed that the high-volume fly ash concrete has slightly higher (7%) endurance limit when expressed as a ratio (ratio of flexural fatigue strength to static flexural strength) compared to plain portland cement concrete. However, the modulus of rupture and fatigue strength were slightly higher for the control concrete. The results further indicated that there was an increase (15 to 30%) in static flexural strength for both the high-volume fly ash concrete and plain concrete beams which were previously subjected to four million cycles of fatigue stresses at their respective fatigue limit load (Tables 3-11 and 3-12).

FATIGUE MODELS
Majority of studies on the fatigue of concrete have been directed toward relating applied cyclic load and fatigue life expressed in terms of number of cycle to failure. This relationship is commonly plotted in a so-called S-N curve (or Wohler curve). It is also generally accepted that
nondimensionalized S-N curve ($f_{\text{max}}/f'_c$ versus log $N$) is independent of the specimen shape, the concrete strength, the curing condition, the age, moisture condition at loading, etc.

Aas-Jakobsen (28) investigated the effect of the minimum stress $f_{\text{min}}$ on the fatigue strength. He reported based on the results taken from S-N curve that the relationship between $f_{\text{max}}/f'_c$ and $f_{\text{min}}/f'_c$ is linear for fatigue failures at $N = 2$ million load cycles, and derived the following expression to determine the tensile fatigue strength of concrete:

$$\frac{f_{\text{max}}}{f'_c} = 1 - \beta(1 - R) \log_{10} N$$

where $R = f_{\text{min}}/f_{\text{max}}$, the fatigue stress ratio; the coefficient $\beta$ is equal to 0.064. The equation is valid only within the range of $0 \leq R \leq 1$.

Based on test results and data reported in literature, Tepfer and Kutti (45) verified Equation 3-4 and found the value $\beta$ equal to 0.0685 for fatigue strength of plain, ordinary, and lightweight concrete in compression. The author, therefore, proposed a new form of Equation 3-4 as:

$$\frac{f_{\text{max}}}{f'_c} = 1 - 0.0685(1 - R) \log_{10} N$$
Tepfer (46) examined S-N curve for plain concrete subjected to pulsating tensile stresses. Based on splitting tests of concrete cubes, the author showed that tensile fatigue strength can be adequately described by Equation 3-5 proposed by Tepfers and Kutti (45).

Oh (70) conducted an experimental investigation to evaluate the fatigue strength of plain concrete subjected to flexural loadings. The simply-supported beam specimens (100 x 100 x 500 mm) were tested in four point flexural loading in which the bottom fiber stress varies from zero to a predetermined maximum stress at a constant rate of 250 cycles/min.

He developed empirical model to describe the flexural fatigue of concrete as:

\[
\frac{f_{\text{max}}}{f'_r} = a + b \log_{10} N
\]

where \(f'_r\) = modulus of rupture of concrete, \(f_{\text{max}}\) = maximum applied stress in fatigue loading, and \(a\) and \(b\) are regression coefficients.

The author reported that \(\beta = 0.069\) for flexural fatigue loading as described by Equation 3-5. The model was found to provide adequate representation of data obtained from different studies (45,46) on splitting-tensile and compressive fatigue strength of concrete.

Hsu (49) developed a more general four-variable S-N-T-R relationship for predicting the fatigue strength of plain concrete. This model
incorporates an additional variable, the dimension of T, which is the period of cyclic loading expressed in seconds per cycle. Since T represents the rate of loading, and the product of T and N represents the duration of loading, this four variable relationship simultaneously accounts for the time effect and the effect of loading rate. Based on the S-N-T-R relationship, the author proposed two equations for the determination of fatigue strength of concrete. For high-cycle fatigue, the equation is expressed as:

\[
\frac{f_{\text{max}}}{f_c} = 1 - 0.0662(1 - 0.556R)\log N - 0.0294\log T
\]

where \(f_{\text{max}}\) = maximum stress in repetitive loading, and \(f_c'\) = static compressive strength, \(R = f_{\text{min}}/f_{\text{max}}\). For low-cycle fatigue, the equation is of the form:

\[
\frac{f_{\text{max}}}{f_c} = 1.20 - 0.20R - 0.133(1 - 0.779R)\log N - 0.0530(1 - 0.445R)\log T
\]

It is well established that many design factors such as material strengths and applied loads are bound to have statistical variability. Therefore, the fatigue design process is, full of uncertainties arising from the numerous assumptions made in analysis and material variability. In general, fatigue test data exhibit substantial scatter and are random.
in nature relative to the static tests. Therefore, it is highly essential to incorporate probability concept to evaluate fracture resistance of concrete structure due to fatigue. There is a lack of information on probabilistic reliability analysis of concrete structures. This analysis requires knowledge of the probability laws of the given structural materials. Oh (70) introduced a probabilistic approach to determine the fatigue reliability of concrete. His fatigue life data on concrete under a given stress level followed the Weibull probability law. The result exhibited that the Weibull distribution law provide a better representation of the experimental data than the log normal distribution, and therefore it can be used to describe the fatigue behavior of concrete. Oh (93) examined the distributions of fatigue life of concrete for various levels of applied stresses. The maximum stress levels used were 85, 75, and 65 percent of the static flexural strength of concrete. All test specimens (100 x 100 x 500 mm) were loaded using the third-point loading system in which the bottom fiber stress varies from zero to a predetermined maximum stress. The rate of constant-amplitude fatigue loading was 250 cycles/min. Table 3-13 shows the fatigue lives for each fatigue stress level \((f_{r_{\text{max}}}/f'_c)\) determined experimentally. The test results indicated that the probabilistic distributions of fatigue life of concrete depended upon stress level and thus the shapes of the Weibull distribution to describe the fatigue life of concrete depended upon levels of applied fatigue stress (Figure 3-38). The author recommended that this effect must be properly taken into account in fatigue reliability analysis to secure better results.
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Plain Concrete With or Without Fly Ash


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Concrete structure such as bridges, pavements, offshore structures, etc. are subjected to dynamic loadings. A knowledge of fatigue behavior of concrete is needed for safe and cost effective design of these structures.

In cementitious composites including concrete with or without mineral admixtures known to have microcracks and/or macrocracks in both matrix and the interface region between matrix and aggregates. The cracks serve as potential sites for the nucleation of dominant cracks during the cycle loadings. High stresses generated at the tip of these flaws or cracks aid in crack growth and propagation under the influence of external stresses. The crack growth continue to occur when subjected to repeated stresses which leads to failure when size of dominant crack(s) exceed the critical size. The critical size would depends upon fracture properties of the material. Compared to metals, very limited amount of information is available concerning rate of crack growth in concrete due to fatigue loading.

Numerous studies have been carried out in the past to establish the effects parameters such as type of loading, rate of loading, rest period, load history (constant, variable and random loadings), air content, water-to-cementitious ratio, superplasticizers, fly ash inclusion, etc. on fatigue behavior of concrete.
Analysis of the results from previous investigations led to the following main conclusions.

1. When fatigue strength of concrete is expressed as percentage of its static strength, it is not substantially influenced by parameters such as strength, air-entrainment, type of aggregate, age, etc. However, beyond certain strength level, the ratio of fatigue strength to static strength may be decreased due to lower fracture toughness of high strength concretes compared to low-strength concretes.

2. Stress-strain behavior depends heavily upon number of repetitions of loads, but this effect becomes insignificant when the applied stress level is small to produce sufficient fatigue damage.

3. Some test results have revealed that concrete hardens due to cyclic loadings, similar to that observed in metal, when applied stress levels are less than its fatigue limit. This may be attributed to crack blunting that occur during the cyclic loadings.

4. Concrete fatigue strength is influenced by the range of cyclic loading. In general, a decrease of maximum stress level and/or stress range enhances fatigue life of concrete.

5. Fatigue strength of concrete remains relatively unattended by the rate of loading when applied loading cycle in the range of 0 - 20 Hz. However, very little is known about behavior of concrete beyond 20 Hz loading cycles.

6. Fatigue strength of concrete depends greatly upon type of loadings.

7. Test results have shown that the Palmgren-Miner hypothesis provides either underestimate or overestimate of fatigue damage that actually occurs in structures due to the loading sequence effects. Hence, a non-linear model is needed to describe fatigue behavior of plain concrete under varying loading conditions.

8. A few investigations have indicated that fatigue life is slightly reduced due to stress reversal effects. This effect is diminished when the stress ratio (R) is greater than zero.

9. Tests have substantiated that rest period between the fatigue loading cycles increase the fatigue life strength of plain concrete significantly. However, this depends greatly upon stress levels, type of cyclic loading, duration of rest periods, etc.

10. Fatigue strength of concrete is significantly influenced by the applied stress gradient. A study showed 15 to 18 percent increase in fatigue strength of eccentric specimens relative
to that of uniformly stressed prisms (17). Based on this study, authors recommended that the fatigue strength of uniformly loaded beams can be assumed as a lower limit of the fatigue life of flexural members.

11. Up to a certain level, concrete fatigue strength increases with age (approximately 3 months), and beyond this the fatigue strength becomes less dependent upon age.

12. The influence of air content on fatigue strength of concrete is investigated to a very limited extent. The fatigue strength decreases with increasing air content in concrete.

13. Substantial interactions occurs between air content and water-to-cement ratio exists on fatigue properties of concrete. Therefore, their combined effects of these variables on fatigue behavior of concrete must be determined.


15. Relatively, very little work has been done to quantify the effects of addition of fly ash to concrete on its fatigue characteristics. A study showed superior compressive and fatigue properties of concrete made with Class C fly ash as compared with the concrete made with a Class F fly ash or without fly ash. In general, flexural fatigue strength of fly ash concrete systems are similar to that for no fly ash concretes of comparable strength.

16. In general, fatigue limit (endurance limit) of plain concrete was found to vary between 50 to 60% of its static strength irrespective of fly ash addition.