An Experimental Investigation on High Frequency Fatigue Behaviour of Concrete Structures Using Mineral Admixtures

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Abstract- *Fatigue is a progressive brittle failure of a structural element under repeated, cyclic or fluctuating loads. Due to the effect of fatigue load on bridge girders, marine structures and tall structures, the structure life is reduced. This paper gives a comprehensive information about the fatigue behaviour of reinforced concrete beam with mineral admixtures. An overview is given about the influence of mineral admixtures on the mechanical behaviour of concrete and the state of damage of the beam due to fatigue. The method of application of fatigue loading on the beam and the parameters to be determined from the test are explained. The influence of mineral admixtures in the propagation of crack and final crack width observed in concrete and steel in the beam after fatigue loading is explained from the literatures. The fatigue life is determined from the relationship between the number of fatigue cycles and the stress developed in the beam due to fatigue loading.*

I. INTRODUCTION

FATIGUE LOAD: Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking under repeated alternating or cyclic stresses of an intensity considerably below the normal strength.The reinforced concrete structures were designed to take the static loads. But in nature, floors subjected to crowd, vehicle vibration in road pavements, traffic load in bridges, wind and wave action in marine structures gives cyclic or fatigue load to the structure.In this paper, fatigue tests of plain concrete under constant-amplitude and stepping-amplitude cyclic loads were carried out.

II. LITREATURE SURVEY

FATIGUE LOADING

Most materials when subjected to cyclic loading over many thousands of repetitions can exhibit lower strengths compared to their static strength, depending on the rate of loading, the stress ratio (rninimum/maximum cyclic stress), the maximum stress and the number of cycles. A highway bridge on a Class A route with a design life of 40 years can experience a minimum of 58 x 10* loading cycles of varying intensities over its life **(OHBDC, 1983).**

FATIGUE BEHAVIOUR OF REINFORCING BARS

As a key component of the reinforced concrete member, it is important to understand the development and propagation of damage resulting from fatigue loading in the reinforcing steel. This has become even more cntical since high strength steel is now used as reinforcement, yet does not exhibit a higher fatigue strength in proportion to its high static strength **(Salah El Din and Lovegrove, 1980).**

FATIGUE BEHAVIOUR ON HSC

Wu Peigang et al studied the axial compression fatigue behaviour of HSC under constant-amplitude and variable-amplitude repeated loads. Based on the tests, fatigue strength and fatigue deformation of HSC under constant-amplitude repeated loading were analyzed, the empirical formula of longitudinal total strain and residual strain of fatigue strength were given, and a formula for judging the fatigue failure by residual strain was put forward.

FATIGUE BEHAVIOUR ON HSC UNDER TEMPERATURE

Li Lijuan et al conducted a high-temperature test on HSC (100 MPa), which studied its appearance, compressive strength, flexural strength and splitting tensile strength after 500℃ and 800℃. HSC after high temperature could occurs bursting phenomenon, with the fire temperature increasing, compressive strength, flexural strength and tensile strength splitting gradually become smaller, microstructure gradually worse, Mainly as follows: the loss of crystal water, cement hydrated e composition occurs when the fire temperature reaches 800℃, the crystal water all lost, cement hydrate all the decomposition, the structure becomes loose

Long T et al studied the fire performance of HSC and compiled the fire test data. It indicated that HSC and plain concrete showed great difference in the temperature range of 20℃ to 400℃.

Ping Cheng et al studied the stress-strain curves of high-strength concrete at 20℃, 100℃, 200℃,400℃, 600℃ and 800℃, and pointed out that the compressive strength of HSC increased with temperature. The compressive strength at 800℃ was about one quarter of its initial strength

III. MINERAL ADMIXTURES

The addition of mineral admixtures such as Fly ash, GGBS, Silica Fume, Bottom ash in concrete may improves the mechanical behaviour of concrete. The mineral admixtures can either be added as pozzolona to cement in powdered form or as partial replacement for fine aggregate with respective to their physical properties. The application of industrial by products as mineral admixtures help in waste utilization .The work herein investigates the high frequency fatigue behaviour of concrete structures, externally strengthened with mineral admixtures.

BOTTOM ASH : It is a granular incombustible residue obtained from the furnace, boilers, and chimneys.It is having similar properties of sand and it can be partially replaced with sand. The increase in the percentage of It for partial replacement sand reduces the workability of concrete. The compressive strength of the concrete containing 30% and 40% It was found to be 108% and 105% at 90 days was more than that of normal concrete. The flexural strength was in the range of 113-118% at 90 days when compared to that of normal concrete at 28 days

FLYASH: Fly ash is a finely powdered coal combustible material collected from the boilers, chimneys. Fly ash is a mineral admixture which is having high pozzolonic properties which can be used in the manufacturing of PPC. Fly ash can be used as mineral admixture in concrete which improves the mechanical properties of concrete. Naik and Singh tested flexural and fatigue strength of beams with C type fly ash shows that increasing the fly ash content from 15% to 50% causes reduction in fatigue strength of the beam.

GGBS: Ground Granulated Blast furnace Slag (GGBS) is one of the mineral admixture which is having pozzolonic property. GGBS can be either used as an ingredient in cement manufacturing or in concrete. Babu and Kumar studied the efficiency of GGBS in concrete shows that increase of 8.6% for 50% and 19.5% for 65% replacement in total cementitious material for achieveing the strength at 28 days for nominal concrete.

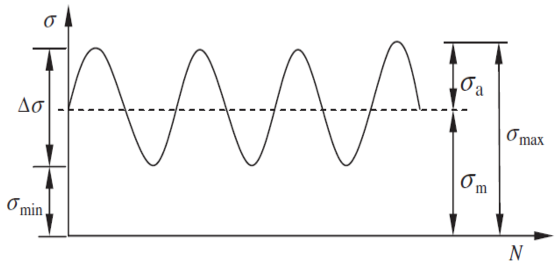
IV. HIGH FREQUENCY FATIGUE TESTS OF PLAIN CONCRETE

The loading frequency for common fatigue tests is usually below 30 Hz, but can reach 100 Hz for high frequency fatigue tests. Under high frequency, the time and cost of reaching the fatigue limit and strength of a material are dramatically reduced. Here, high frequency fatigue tests with constant amplitude and stepping amplitude were conducted.

V.HIGH FREQUENCY FATIGUE TESTS UNDER CONSTANT-AMPLITUDE AND STEPPING-AMPLITUDE CYCLIC LOAD

STATIC LOADING: For these tests, 33 cylindrical C30 concrete specimens, 70 mmin diameter by 100 mmhigh were prefabricated. They were manufactured in plastic moulds and were maintained for 28 days at a temperature of 20 ± 3 _C before being tested. From the static loading tests it was found that the ultimate loading capacity of the cylindrical specimens was Fu = 112.11 kN, so the axial compressive strength is fco = 29.1 MPa. The compressive strength of the cubic samples was fcu = 36.6 Mpa, and the elastic modulus amounted to Ec = 4.73 -104 MPa.

CONSTANT-AMPLITUDE CYCLIC LOADING TESTS: The test parameters included the biggest stress σmax, the smallest stress σmin, the mean stress σm, and the stress amplitude σa. The relationship among the parameters is shown in Fig. Table indicates the loading conditions for the high frequency fatigue tests under constant-amplitude cyclic loads.



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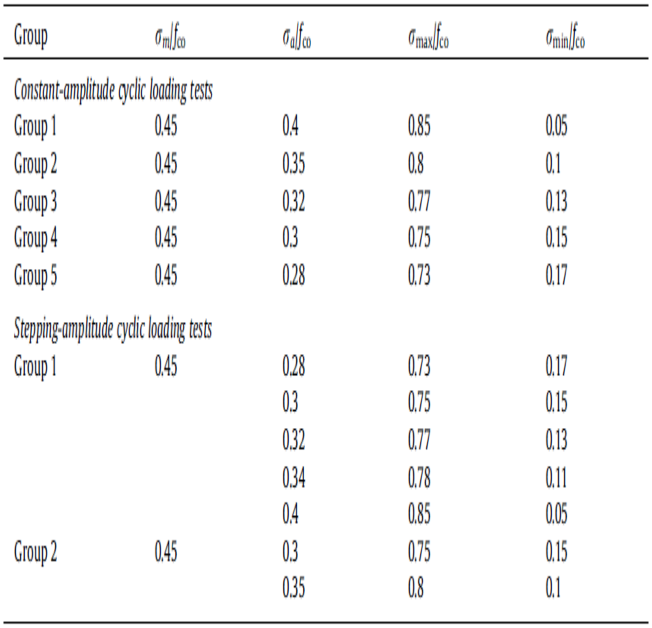


Group	σ_m/f_{co}	σ_a/f_{co}	σ_{max}/f_{co}	σ_{min}/f_{co}
Constant-amplitude cyclic loading tests				
Group 1	0.45	0.4	0.85	0.05
Group 2	0.45	0.35	0.8	0.1
Group 3	0.45	0.32	0.77	0.13
Group 4	0.45	0.3	0.75	0.15
Group 5	0.45	0.28	0.73	0.17
Stepping-amplitude cyclic loading tests				
Group 1	0.45	0.28	0.73	0.17
		0.3	0.75	0.15
		0.32	0.77	0.13
		0.34	0.78	0.11
		0.4	0.85	0.05
Group 2	0.45	0.3	0.75	0.15
		0.35	0.8	0.1

STEPPED AMPLITUDE CYCLIC LOADING

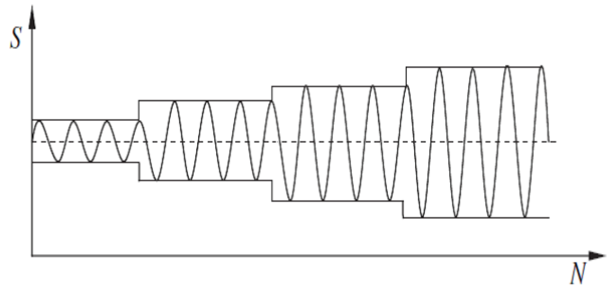
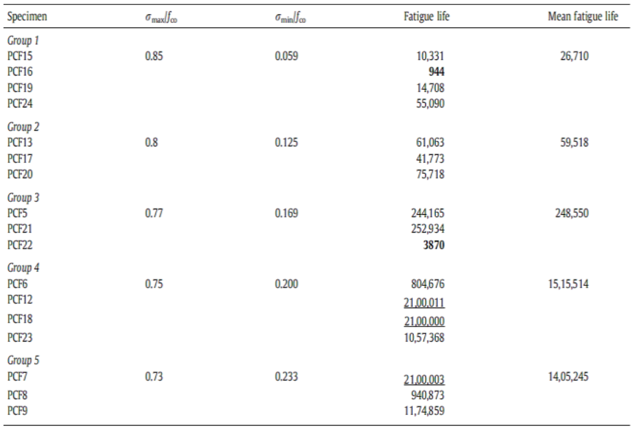


Fig. 3. Schematic diagram for stepping-amplitude fatigue test.

TEST RESULT

Constant-amplitude cyclic loading tests were carried out at five stress levels using 17 specimens while stepping-amplitude cyclic loading tests were divided into two groups using eight specimens.

The fatigue life of the specimens is shown in Table . Among the data, two are invalid (the tests were unsuccessful), indicated in bold, three exceeded the limit of fatigue life indicated with an underline. The results obtained from the stepping-amplitude cyclic loading test were unsatisfactory and are not listed here.



Specimen	σ_{max}/f_{co}	σ_{min}/f_{co}	Fatigue life	Mean fatigue life
Group 1				
PCF15	0.85	0.059	10,331	26,710
PCF16			**944**	
PCF19			14,708	
PCF24			55,090	
Group 2				
PCF13	0.8	0.125	61,063	59,518
PCF17			41,773	
PCF20			75,718	
Group 3				
PCF5	0.77	0.169	244,165	248,550
PCF21			252,934	
PCF22			**3870**	
Group 4				
PCF6	0.75	0.200	804,676	15,15,514
PCF12			<u>21,00,011</u>	
PCF18			<u>21,00,000</u>	
PCF23			10,57,368	
Group 5				
PCF7	0.73	0.233	<u>21,00,003</u>	14,05,245
PCF8			940,873	
PCF9			11,74,859	

VI. HIGH FREQUENCY FATIGUE FAILURE MECHANISM OF THE M30 CONCRETE SPECIMENS

An analysis of the results of the high frequency fatigue tests showed there are two main modes of fatigue failure:

(1) <u>Vertical failure: </u>During loading it was noted that the loading plates of the fatigue testing machine were the same length as the end planes of the concrete specimen. Horizontal fatigue tensile stress will cause vertical micro-cracks to begin and then develop into vertical macro-cracks which will cause the specimen to rupture.

(2) <u>Conical failure: </u>Cracks in the concrete specimens did not develop along the loading direction during loading. The final rupture macro-cracks look like cones.

The results of fatigue testing showed that vertical failure was the main failure mode. With the stepping-amplitude cyclic loading tests, because vibration occurred over a long period of time, surface cracks and internal cracks were fully developed and some specimens were crushed

(b)

(a)

VII. THE NON-LINEAR ACCUMULATIVE HIGH FREQUENCY FATIGUE DAMAGE FORMULA OF M30 PLAIN CONCRETE

The following formula for computing the accumulated fatigue damage and predicting the residual fatigue life.

$$D_t = s_i(n_i)\frac{n_i}{N_{fi}}$$

In the equations listed above, Smax is the maximum stress level and R is the correlation coefficient.Eq is not only suitable for computing the fatigue damage under constant-amplitude cyclic loads, but for analysing the development of fatigue damage under stepping-amplitude cyclic loads.

$$S_{\max} = 0.73 : s(n) = 2.1154n^{-0.988},\ R = 0.9997;$$

VIII. EXPERIMENTAL SETUP

LOADING ARRANGEMENT

The beam specimens were tested for four point bending at one third of the span from either side of the support or three point bending in the mid span.

The fatigue loading was given to the beam by actuator using a computer controlled system.

The frequency of the loading is adopted with respect to the actuator capacity.

Before applying the fatigue loading, 5 -10 kN static load was loaded and reduced repeatedly to improve the bearing contact.

Then, beam specimen was adjusted to the average fatigue force, fatigue loading started. The fatigue test was paused and actuator is unloaded after the completion of fatigue cycles. After the residual deformation was stable, the beam n was monotonically loaded to the upper limit value of fatigue load under step loading of 10 kN and the deflection data was collected at each step of monotonic loading. When fatigue fracture of any one of the tensile reinforcing bars occurred, the actuator immediately unloaded for protection to prevent the beam specimens from being secondary loaded after fatigue failure.

IX. RESULTS AND DISCUSSIONS

- The RC beams subjected to fatigue loading fails by the yielding of reinforcement in tension zone followed by the crushing of concrete in the compression zone.
- The number of fatigue cycles the beam withstands determines the fatigue strength of beam.
- Most of the tests were stopped after 2,000,000 cycles if the beam resists in order to save energy and time.
- Control beams resists fatigue failure up to 2 million cycles and after that static load is applied up to failure. The control beams also shows ductile failure in static loading.
- The static failure load applied after 2 million cycles were same as that of the actual static failure load 148 kN.
- It was showed that fatigue effect had no substantial influence on the static performance of RC beams without corrosion
- We studied the flexural fatigue behaviour in high volume fly ash concrete beams of size 500mm X 75mm X 100mm under two point loading.
- Constant amplitude sinusoidal wave loading was applied with frequency of 4Hz having maximum stress value as 0.8fck and minimum loading as 10% of maximum load.
- The failure was found to be brittle in nature. The fatigue strength for high volume fly ash concrete was higher when compared to conventional concrete.

LOAD RANGE

- The variation in the load range may affect the fatigue behaviour of the beam irrespective of its dimensions, support conditions, etc.
- We tested the fatigue behaviour of reinforced beams with various load range.
- It is found that increase in load range results in reduction of fatigue life.
- These beams shows that the fatigue strength at one million cycles reaches 50% of static load**.**

CRACK PROPOGATION

Concrete failure may be possible due to the presence of air voids, honey combs due to improper compaction, voids due to shrinkage. These voids may be prone to development of cracks due to the cyclic loading. The fatigue cracks were flexural in nature as they occurs in pure bending region. The crack width increases with increase in the number of fatigue cycles. A few cracks were found outside the pure bending section due to the progression of fatigue cycles

We tested T beams under fatigue loading, within the constant-amplitude fatigue test, the cracks in the beam included normal cracks located in the pure-bending segment and bending shear oblique cracks. The crack depth reached to the half-height of the beam at the first loading and the cracks were distributed symmetrically along the span direction on both sides of the cross section.

DEFLECTION UNDERFATIGUE

The cracks were formed and closes after completion one cycle of fatigue loading and the deflection at the mid span and quarter span due to crack formation were recorded in the LVDT’s.

The flexural stiffness of the beam reduces due to the rapid change in the mid span deflection.

DEFLECTION UNDER STRAIN

The stiffness of the beam reduces due to the application of load. Cyclic load on the beam causes an initial deformation in the beam which causes strain in steel. The strain in concrete and steel were obtained from the strain gauges fixed in compression zone, mid half side of the beam and in mid span of tension reinforcement and near the support at compression reinforcement respectively. The strain value in steel increases with the variation in the mid span deflection due to fatigue loading

FLEXURAL BEHAVIOUR OF CONCRETE

- The addition of mineral admixture in concrete may influence the flexural property.
- The mechanical properties of the concrete with waste bottom ash as replacement for natural aggregate using M40 grade of concrete.
- The results shows that increase in the percentage of replacement may reduce the flexural strength of the concrete when compared to conventional concrete
- For 100% replacement of bottom ash for sand reduces 27% of flexural strength. Optimum results were found for 20% replacement of bottom ash for fine aggregate.
- The flexural fatigue strength of the concrete with Fly ash and GGBS as additives with cement and crushed Basalt aggregate for different mixes.
- Two point fatigue loading is provided with two maximum stresses as 0.7 and 0.5 of compressive strength of concrete and 15% maximum load as minimum load.
- The results shows that the optimum addition of fly ash and GGBS increases the mechanical properties of concrete.

X. CONCLUSION

Through the experimental research work and theoretical analysis, the following conclusions can be drawn:

(1) The two main failure modes of plain concrete in high frequency fatigue tests are vertical failure and conical failure.
(2) The results of low frequency fatigue tests can be calculated from the results of high frequency fatigue tests using the corrected high frequency coefficient .
(3) It is more reasonable to establish a P–S–N fatigue equation that corresponds to a certain failure probability.
(4) Research work contributes to a discussion of the characteristics of a fibre reinforced concrete column in high frequency.
(5) The fatigue behaviour of the reinforced concrete beams with addition of mineral admixture was studied. The addition of mineral admixtures up to an optimum extend increases the mechanical properties of the concrete.
(6) The fatigue strength of the beam is determined from the number of fatigue cycles the beam can withstand up to failure due to the application of fatigue loading.
(7) The deflection of the beam under the fatigue loading was determined using LVDT or dial gauge
(8) The strain in the concrete and steel was measured using the strain gauges.
(9) The addition of mineral admixture in an optimum percentage will improve the flexural fatigue strength of the concrete.

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