



International Journal of Emerging Technology and Advanced Engineering
 Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 11, November 2012)

Fatigue Analysis of High Performance Cement Concrete for Pavements using the Probabilistic Approach

Suresh Kumar K.S.¹, Kamalakara G.K.², Sagar Kamble³, Amarnath M.S.⁴

¹Research Scholar, Department of Civil Engineering, Bangalore University, Bangalore, India

²M.E.Student, Department of Civil Engineering, Bangalore University, India

³Assistant Professor, Govt. Engineering College Karwar, Karnataka, India

⁴Professor Highway Engineering, Bangalore University, India

Abstract— Cement concrete pavements are designed for flexural fatigue loading due to traffic. Due to its numerous advantages high performance cement concrete is finding its way in pavement construction. This paper investigates the fatigue strength of High Performance Cement Concretes subjected to flexural loading. Fatigue studies are conducted on these concretes to obtain the fatigue lives at various stress levels. Static flexural strength tests are conducted to determine the static failure loads on prism specimen. From the experimental studies carried out, the number of load repetitions to failure on the concretes under study is determined for three stress ratios. From the data obtained S-N curves are developed using linear regression models considering log normal distribution as is being presently adopted. Recent literature shows that weibull distribution is found to have more convincing physical features than the lognormal distribution to describe the fatigue behavior of concrete. To incorporate the probability of failure, weibull distribution is considered and P-S-N diagram are developed. It is observed that addition of fly ash and silica fume improves the fatigue performance of concrete by 48% and 83% at a stress level of 0.75.

Keywords— Fatigue, Flexure, High Performance Cement Concrete, Rigid Pavement, Statistical Distributions

I. INTRODUCTION

Fatigue is the failure of a component as a result of cyclic stress. The failure occurs in three phases: crack initiation, crack propagation, and failure. The duration of each of these three phases depends on many factors including fundamental raw material characteristics, magnitude and orientation of applied stresses, processing history, etc.[1] Fatigue failures often result from the magnitude of applied stress significantly below those necessary to cause static failure. In recent years high performance cement concrete is being used in the construction of rigid pavements. As rigid pavements are designed for fatigue, considerable interest is shown in the fatigue strength of pavements. Hence, the study of the effects of repeated loads on high performance concrete pavements are to be studied in particular.

ACI 215R-74 [2] defines Fatigue as “a process of progressive permanent internal structural change in a material subjected to repetitive stresses”. These changes may be damaging and result in progressive growth of cracks due to repeated application of traffic loads, progressive fatigue damage takes place in the cement concrete slab in the form of gradual development of micro cracks and complete fracture if the stress repetitions are sufficiently large.

A. Research Significance

Very little literature has been reported on research which addresses the behavior of high performance cement concrete under flexural fatigue loading. The present investigations are conducted on High Volume Fly Ash Concrete (HVFAC), Silica Fume Concrete (SFC) and Pavement Quality Concrete (PQC).

Log normal distribution is generally considered for developing S-N curves to determine the number of repetitions to failure under fatigue loading. Since most of the fatigue studies on concrete have mainly focused on simple S-N relationships, little attention has been paid to probabilistic reliability analysis for concrete fatigue. In this study Weibull distribution is considered to impart probabilistic reliability against fatigue failure. An effort is made to develop relationships between stress level, fatigue life and probability of failure.

II. MIX PROPORTIONS AND STRENGTHS OF HPC

Ordinary Portland Cement _ 53 grade, Class _ F Fly Ash, Silica fume 920_D grade are used as binders, 20 mm and down graded crushed granite stone coarse aggregates and river sand conforming to IS 383 1970 reaffirmed in 2008 are the materials used in this study. The mix proportions are shown in Table 1. Both compressive and flexural strength tests are carried out as per IS 516 1959 reaffirmed in 1999. Cube specimen of size 150 x 150 x 150 mm are cast and tested to determine compressive strength.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 11, November 2012)

Prisms of size 100 mm x 100 mm x 500 mm are cast and static flexural strength tests conducted to determine the static failure loads on the specimen. Compressive and Flexural strengths obtained are shown in Table 1.

TABLE I
MIX PROPORTIONS AND STRENGTH OF HPCS

Mix	PQC	HVFAC	SFC
Water / binder ratio	0.39	0.39	0.46
Cement kg/m ³	405	208.5	370
Fly ash kg/m ³	0	208.5	0
Silica fume	0	0	32.17
Super Plasticiser %	0	1.25	0.3
Fine aggregate kg/m ³	750	565	814.35
Coarse aggregate type-I kg/m ³	720	786	676.36
Coarse aggregate type-II kg/m ³	355	387.00	332.64
Water kg/m ³	150	162.53	170.2
Compressive Strength (MPa)	48.23	48.82	49.48
Static Flexural Strength (MPa)	4.76	4.93	5.75

Prism specimen are loaded and tested in accordance with ASTM Test Method C 78. The third point loading method with forces applied perpendicular to the beam without eccentricity is adopted. Accelerated cyclic fatigue testing equipment is used to conduct flexural fatigue test. The schematic diagram of the test arrangement is showed in Figure 1 and a snap shot of the test set up is shown in Figure 2. To simulate realistic traffic loading half sine wave form loading with a frequency of two cycles per second is applied repetitively on the specimen.

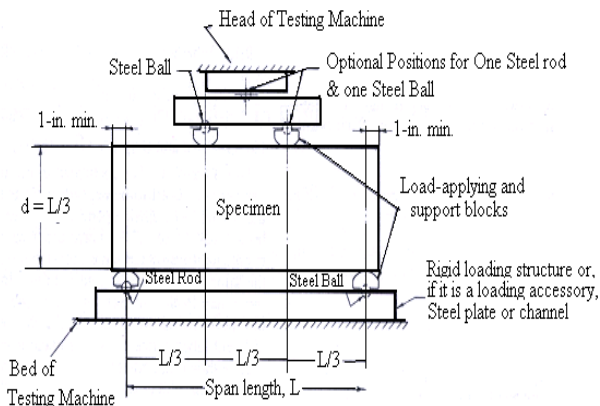


FIGURE 1
FLEXURAL FATIGUE TEST ARRANGEMENT

From the experimental studies carried out, the number of repetitions to failure is determined for three stress levels 0.65, 0.70 and 0.75 for PQC and HVFAC and 0.65, 0.75 and 0.85 for SFC.



FIGURE 2
FLEXURAL FATIGUE TEST SET UP

III. ANALYSIS OF FATIGUE TEST DATA

From the fatigue test data obtained for the three concretes under investigation S-N curves are developed using linear regression models, considering log normal distribution. The linear regression model is of the form ($y = ax + c$) in which stress ratio (S) is taken on Y-axis and Log (N) values are taken on the X-axis. The scatter diagram of the test results for PQC, HVFAC and SFC are shown in Figure 3. The linear relationship obtained from the trend lines for PQC, HVFAC and SFC along with the R² values are shown in equations 1, 2 &3.

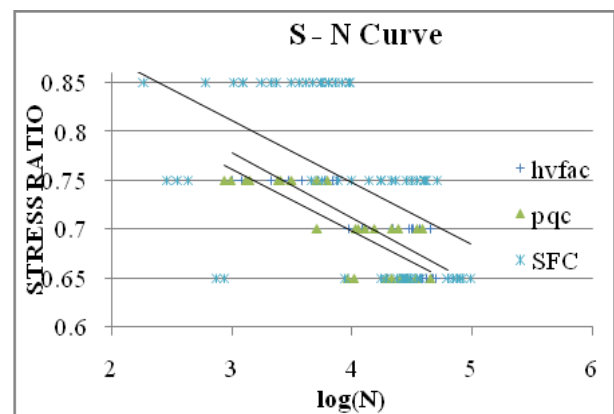


FIGURE 3
SCATTER DIAGRAM

$$\log(N) = \frac{0.949 - SR}{0.063} \quad \text{PQC1}$$

$$R^2 = 0.638$$

$$\log(N) = \frac{0.978 - SR}{0.066} \quad \text{HVFAC2}$$

$$R^2 = 0.718$$

$$\log(N) = \frac{1.001 - SR}{0.063} \quad \text{SFC3}$$

$$R^2 = 0.317$$

A Comparison of Fatigue Life Values

The developed linear regression models are compared with the fatigue model given in IRC: 58- 2011 [3]. The model suggested by IRC 58 – 2011 is shown in equation 4. IRC – 58 2011 - Guidelines for the design of plain jointed rigid pavements for highways is the procedure that is presently being used in India for the design of rigid pavements.

$$\log(N) = \frac{0.9718 - SR}{0.0828} \quad \text{IRC 584}$$

The values of fatigue life at different stress ratios from the developed fatigue models are compared with those given in IRC 58: 2011 and shown in Table 2. Figure 4 shows the S-N curves developed using results from the present investigations. The percentage increase in fatigue life in PQC, HVFAC and SFC are compared with the IRC values and are shown in Table 3

It is observed that at 65% stress level, increase in number of repetition to failure is 27% in HVFAC, 38% in PQC and 42% in SFC when compared to IRC values. The number of load repetitions to failure in SFC is the highest. It is also observed that the percentage increase in fatigue life is higher at higher stress ratios in SFC and HVFAC..

TABLE 2
COMPARISON OF FATIGUE LIVES

Stress Ratio 'SR'	Number of repetitions to failure 'N'			
	IRC 58	HVFAC	PQC	SFC
0.55	1.24x10 ⁵	2.38x10 ⁵	8.39x10 ⁵	1.23x10 ⁷
0.6	3.09x10 ⁴	4.48x10 ⁵	1.39x10 ⁶	2.02x10 ⁶
0.65	7.7x10 ³	8.47x10 ³	2.31x10 ⁵	3.32x10 ⁵
0.7	1.97x10 ³	1.6x10 ⁴	3.8x10 ⁴	5.45x10 ⁴
0.75	477	3.0x10 ³	6.4x10 ³	8.93x10 ³
0.8	119	568	1054	1466
0.85	30	107	174	240

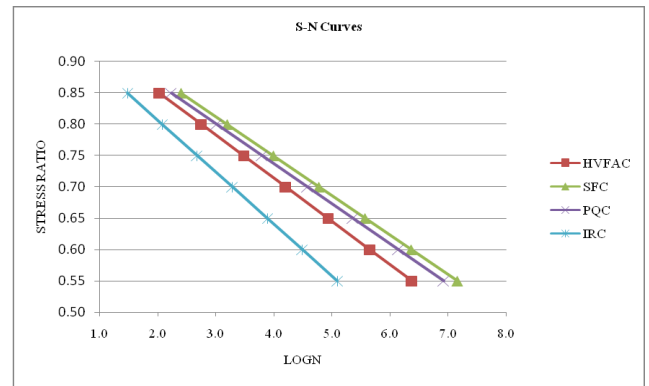


FIGURE 4
COMPARISON OF S – N CURVES

TABLE 3

Stress Ratio	Percentage increase in fatigue life compared to IRC 58		
	HVFAC	PQC	SFC
0.55	25	36	39
0.65	27	38	42
0.75	29	42	48
0.85	37	52	61

B Probability Analysis

Probability is defined as a measure of what is expected to happen on the average, if a given observation or measurement is repeated a large number of times under identical conditions. The fatigue behavior of concrete is generally characterized by the S-N curve. The fatigue data of concrete shows great variability due to the material's heterogeneity. The low R² values of the models developed, shown in equations 1, 2 and 3 and the scatter plot shown in Figure 3 justify the great variability in the fatigue test results. Researchers have lately shown that the fatigue-life distribution of concrete is found to follow the Weibull distribution better than the log normal distribution. The adoption of the lognormal distribution has been primarily based on arguments of mathematical convenience. However, as pointed out by Oh B.H [4], the hazard function for lognormal distribution decreases with increasing fatigue life, which violates the physical phenomenon of progressive deterioration of materials resulting from the fatigue process. Oh B.H found that the Weibull distribution function may be compatible with the fatigue behaviour. The Weibull distribution is based on physically more convincing arguments. The applicability of the Weibull distribution to concrete fatigue is, therefore, investigated in the following section.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 11, November 2012)

The verification of this distribution is attempted and the parameters of the distribution are determined from the experimental data at different fatigue stress levels. The methods, generally adopted to estimate the distribution parameters are graphical method, method of moments and method of maximum likelihood. In this study the graphical method is used and the values of the two parameters ‘ α ’ and ‘ u ’ from weibull distribution are calculated.

Where ‘ α ’ = Shape parameter and
‘ u ’ = characteristic extreme value

The two parameters of weibull distribution is shown in Table 4

TABLE 4.
WEIBULL DISRIBUTION ‘ α ’ AND ‘ u ’ VALUES

Type of Concrete	STRESS RATIO					
	0.65		0.70		0.75	
	α	u	α	u	α	u
PQC	1.84	28904	1.52	22763	1.35	3062
HVFAC	2.87	46589	1.86	31409	1.30	4915

Type of Concrete	STRESS RATIO					
	0.65		0.75		0.85	
	α	u	α	u	α	u
SFC	0.76	49215	0.63	24240	0.78	792

The number of repetitions to failure as obtained by weibull distribution is shown in Table 5

TABLE 5
N VALUES FROM WEIBULL DISTRIBUTION

Stress ratio	Number of repetitions to failure		
	HVFAC	PQC	SFC
0.85	426	214	1000
0.75	5660	3205	12915
0.65	75232	48123	166810
0.55	1000000	722476	2154435

The Weibull distribution has been employed here to incorporate the failure probability into the S-N relationships of PQC, HVFAC and SFC. As the fatigue-life data of PQC, HVFAC and SFC has been shown to follow the two parameter Weibull distribution, it can be used to calculate the fatigue lives corresponding to different failure probabilities.

Using the values of Weibull distribution parameters α and u , equation 5 can be used to calculate fatigue lives of PQC, HVFAC and SFC corresponding to different failure probabilities (i.e., Pf = 0.05, 0.10, 0.20, 0.30, 0.40, 0.50). The fatigue lives thus obtained are listed in Tables 6 to 8.

$$N = \ln^{-1} \left[\frac{\ln \left\{ \ln \left(\frac{1}{1 - Pf} \right) \right\} + \alpha \ln(u)}{\alpha} \right] \dots\dots 5$$

Where,
 α = Shape parameter
 u = characteristic extreme value
Pf= failure probability
N=fatigue lives

TABLE 6
FATIGUE LIVES AT DIFFERENT PROBABILITIES OF FAILURE

Probability of failure	PQC		
	S=0.65	S=0.70	S=0.75
0.05	5753	3225	339
0.10	8508	5179	578
0.20	12792	8485	1008
0.30	16505	11552	1427
0.40	20064	14632	1862
0.50	23684	17886	2334

TABLE 7
FATIGUE LIVES AT DIFFERENT PROBABILITIES OF FAILURE

Probability of failure	HVFAC		
	S=0.65	S=0.70	S=0.75
0.05	16551	6361	500
0.10	21269	9367	870
0.20	27625	14023	1550
0.30	32530	18044	2224
0.40	36867	21888	2932
0.50	41004	25791	3708

TABLE 8
FATIGUE LIVES AT DIFFERENT PROBABILITIES OF FAILURE

Probability of failure	SFC		
	S=0.65	S=0.75	S=0.85
0.05	16316	3174	18
0.10	24917	5195	45
0.20	38745	8683	116
0.30	51054	11970	212
0.40	63066	15306	335
0.50	75468	18862	496

From linear regression model developed it is observed that number of repetitions to failure for SFC is higher than PQC and HVFAC values. By incorporating the probabilistic failure models the number of repetitions to failure for a desired reliability can be obtained.

IV. CONCLUSIONS

1. The model developed in this study can be used for estimating the cumulative fatigue life while designing high performance cement concrete pavements.
2. As the number of repetitions to failure in SFC is more when compared to PQC and HVFAC, it can be advantageously in the construction of high traffic corridors.

3. The Pf -S-N diagrams can be used to obtain the flexural fatigue strength of PQC, HVFAC and SFC for the desired reliability levels.
4. Adopting reliability analysis in the design of pavement for arriving at probability of fatigue failure is a better option as it is more conservative when compared to linear regression model.

REFERENCES

- [1] Payman Ameen & Mikael Szymanski, 2006. "Fatigue in Plain Concrete, Phenomenon and Methods of Analysis", Chalmers University, Goteborg, Sweden,
- [2] ACI 215R 74, 1997 Considerations for Design of Concrete Structures Subjected to Fatigue Loading.
- [3] IRC 58 2011, Guidelines for the design of plain jointed rigid pavements for highways.
- [4] Byung Hwan Oh, 1991 Fatigue life distributions for various stress levels of concrete, ACI Materials Journal.