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Laboratory Investigations on Behavior of High Volume Fly Ash Concrete Composite Sections under Flexural Fatigue Loading

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ABSTRACT

The understanding of the behavior of a concrete road under fatigue loading is vital for the design and the performance prediction. A lean concrete sub base is used, especially in case of higher traffic intensity, for concrete roads for effective distribution of stresses in the pavement and sub grade. But there are apprehensions regarding utilization of bond between pavement quality concrete and lean concrete for design of rigid pavements. The present investigation presents a study on behavior of high volume fly ash concrete composite sections under flexural fatigue loading. A cement replacement level of 60% with low calcium fly ash was used for both pavement and lean concretes. A total number of 50 composite beam sections were tested under constant amplitude non reversed cyclic loading. Fatigue life distribution followed lognormal distribution at all the stress levels. Relation between stress level and fatigue life was developed for composite section. Bond between two layers of concretes proved to be beneficial from the criteria of load carrying capacity and fatigue behavior.

Keywords: *Composite section, Dry lean high volume fly ash concrete, Flexural fatigue, Pavement quality high volume fly ash concrete.*

1. INTRODUCTION

A dry lean concrete (DLC) sub base is generally recommended for modern concrete pavements, particularly in case of high intensity traffic. Compared to other types of sub base material the lean concrete sub base is much stiffer during different seasons of the year. DLC layer helps in distribution of wheel load stresses much effectively and in turn reducing the thickness of pavement quality concrete. The bond between pavement quality concrete and lean concrete helps in reducing the stresses generated due to increased flexural stiffness. The lower cement content in DLC makes it an economically viable option. But there are concerns expressed over propagation of crack generated in DLC into pavement quality concrete. Hence current Indian codal provisions [1] suggest a separation layer between DLC and overlaying concrete. Behavior of fully bonded pavement quality concrete and DLC layers is still on an experimental stage. Many researchers have carried out studies on developing fatigue models for plain concrete. Majority of the researchers [2]-[4] have developed the fatigue model relating the stress level (S) which is defined as the ratio of maximum stress applied in cyclic loading to static flexural strength, to number load cycles to failure (N), termed as fatigue life. This relation is commonly referred as Wholer equation. The second form of fatigue model given by Vesic et al [5] and Treybig et al [6] is a power equation relating S and N. Jakobsen et al [7] included the effect of ratio of minimum stress to maximum stress in cyclic loading, which is known as stress range (R), in the S-N relation for fatigue. Hsu [8] developed a more general expression for fatigue strength involving four variables i.e., S, N, R and period of cyclic loading (T). But the most commonly used fatigue model for design of concrete pavements is the one given by Wholer equation. The high volume fly ash concrete (HFC) is one specific type of fly ash concrete with minimum cement replacement level of 50% with fly ash [9], lower water to cementitious materials ratio (W/CM), and lower cement contents. Limited studies [10-12] are available on fatigue behavior of HFC. Ramkrishnan et al [12] have developed an S-N relation for HFC with cement replacement level of 58% using third point flexural fatigue loading at a frequency of 20Hz.

In the development of S-N model it has been assumed that the non dimensional term ‘S’ eliminates the influence of static ultimate strength of concrete and hence eliminates the effect of water-cement ratio, type and gradation of aggregate, type and amount of cement, age of concrete. But there are concerns over influence of static strength of concrete on S-N relation due to variation in fracture toughness. There is little literature available on behavior of layered systems made up of dissimilar concretes under fatigue loading. Lee et al [13] have studied fatigue behavior of hybrid layered concrete made up of latex concrete and conventional concrete overlay. But there is no literature available on behavior of composite sections made up of pavement quality HFC and dry lean HFC.

2. RESEARCH SIGNIFICANCE AND SCOPE

In this work an attempt has been made to study the bonding between high volume fly ash concrete (HFC) and lean high volume fly ash concrete (LHFC) under both static and flexural fatigue loading. In the first stage of the work, mix proportions for HFC and LHFC were obtained from trial mixes. In the present investigation a cement replacement level of 60% with low calcium fly ash was used for both types of concrete. In the second stage fatigue strength studies were conducted on composite beam sections made up of HFC and LHFC under constant amplitude non reversed cyclic loading. From the fatigue test results S-N relations were developed for composite sections by carrying out statistical analysis. A total number of 50 composite beam specimens were tested.

3. LABORATORY INVESTIGATIONS

3.1. Materials

The ordinary Portland cement from single batch was used in the present investigation. The coarse fraction consisted of equal fractions of crushed stones of maximum size 20mm and 12mm confirming to gradation specified by codal provisions [14]. Low calcium fly ash satisfying the criteria of fineness, lime reactivity and compressive strength requirements [15] has been used in the investigation. Properties of fly ash used are shown in table 1. Fine aggregate used was natural sand with maximum particle size of 4.75mm confirming to zone-II gradation specified by Indian codal provisions [14]. The Polycarboxylic based superplasticizer was used as water reducing admixture to get the desired workability in case of HFC. The optimum dosage of superplasticizer was fixed by carrying out compaction factor test. Since the mix was sticky target compaction factor was kept in the range of 0.9 to 0.91.

Table 1: Physical properties of fly ash

Characteristics	Laboratory value	Requirements as per IS 3812
Particles retained on 45µ IS sieve (wet sieving) in percent	29	Max 34
Lime reactivity in N/mm^2	4.9	Min 4.5
Compressive strength at 28 days	88% of the strength of corresponding plain cement mortar cubes	Minimum of 80% of the strength of corresponding plain cement mortar cubes
Specific gravity	2.01	--------

3.2. Mixture Proportions

The trial mix for HFC was developed to achieve M35 grade concrete satisfying the criteria of minimum flexural strength for pavement concrete i.e., 3.8N/mm^2 [16] at cement replacement level of 60% with water to cementitious material ratio (w/cm) of 0.3. For LHFC a trial mix using cement replacement level of 60% with fly ash and yielding M10 grade concrete was developed. Mixture proportions for both the concrete mixes are shown in table 2.

3.3 Test Specimens

Cube specimens of size 150mm×150mm×150mm were used for determining the compressive strength. The beam specimens of size 75mm×100mm×500mm confirming to published literature [12] and ASTM C 78 [17] were used by the authors [18] for static and fatigue testing in the case of HFC. Hence the dimension of composite beam section for static and flexural testing was kept at 75mm×200mm×500mm. Top 100mm depth was made up of HFC and bottom 100mm depth was made up of LHFC. Bond between HFC and LHFC was achieved by using unfinished top surface of LHFC and casting the HFC above that after the setting time of LHFC and no additional treatments were used. A typical composite beam specimen used for static and fatigue tests is shown in figure 1. A total number of 50 beam specimens were used for fatigue testing and 6 number of beam specimens were used for static flexural testing. Effective span of beam sections was kept at 400mm for both the tests. All the composite specimens failed within the middle third thus justifying the depth and span combination used for the testing.

Table 2 Mixture proportions of concrete mixes

Mix Designation / Mixture Components	HFC	LHFC
Cement (OPC 53 grade) in kg/m^3	176	88
Class F fly ash in kg/m^3	264	132
Water in kg/m^3	132	143
Superplasticizer in liter/m^3	3.5	0.0
Saturated surface dry sand in kg/m^3	858.2	660
Saturated surface dry coarse aggregate in kg/m^3	1059	1100

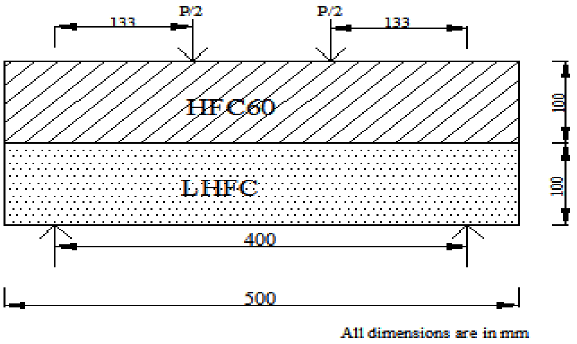

Figure 1: Beam specimen used for static and fatigue test

3.4 Test Procedure and Test Results

3.4.1 Static Testing

All the strength properties were determined after a curing period of 28days. Static compressive strength and flexural strength values for HFC and LHFC are shown in table 3. The values of ultimate static flexural load for HFC and composite sections are also tabulated in table 3. The ultimate flexural stress for composite section can be calculated using equivalent area concept. In the equivalent area concept the equivalent width of LHFC can be found by multiplying the actual width by the ratio of modulus of elasticity of LHFC and HFC. The moduli of elasticity of LHFC and HFC were determined by pulse wave velocity technique and the values are tabulated in table 3. The advantage of a composite system can be seen in the increase in the ultimate flexural load value. The increase in ultimate flexural load value for composite section was 53.5% when compared with that of HFC section.

Table 3: Mechanical Properties of Concrete Mixes

Property of concrete/ Type of concrete	28 day characteristic cube compressive strength* in MPa	28 day Ultimate Flexural Load in Static Test in kN*	28 day characteristic static flexural strength* in MPa	Modulus of Elasticity in GPa*
HFC	40.8	9.9	5.3	42.1
LHFC	14.5	4.2	2.2	15.2
Composite Section	-----	15.2	----	----

* Average value of six specimens

3.4.2 Fatigue Testing

Fatigue test specimens were tested under one-third point loading with frequency of loading as 4Hz. Since the present investigation was aimed at pavement application non reversed cyclic loading was used. Fatigue test set up is shown in figure 2. At a particular stress level amplitude of the fatigue loading was maintained constant through out the testing. Minimum stress in fatigue loading was maintained at 1% of maximum stress. Minimum stress was used mainly to prevent any possible movement of specimens at support during testing and to simulate residual stresses in the pavement to a certain degree. A typical loading pattern is shown in figure 3. All the specimens failed due to propagation of a single vertical crack through the depth of the composite section. The nature of failure was brittle. But for few specimens the initiation of failure was identified by development of crack in the LHFC layer and extension of crack across the full depth took 10 to 15 minutes of time. For these specimens the number of fatigue cycles at the instant of appearance of crack was considered as fatigue life. A typical specimen failed in fatigue loading is shown in figure 4. Fatigue test results for composite sections are tabulated in table 4. Fatigue life values have been arranged in the increasing order so as to facilitate probability analysis.

Figure 2: Flexural fatigue test setup

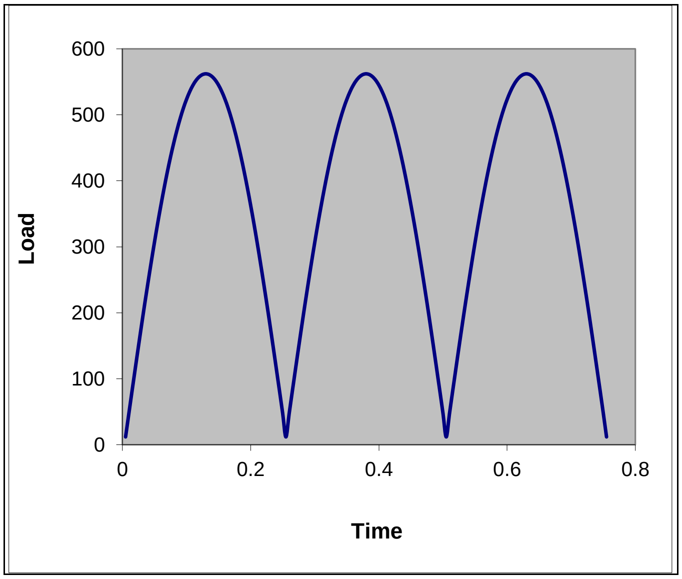

Figure 3: Typical constant amplitude fatigue Loading

Figure 4: Typical failure pattern of composite beam under constant amplitude fatigue loading

Table 4: Fatigue life of composite sections at different stress levels

Stress Level (S) /Test specimen no.	0.80	0.75	0.70	0.65	0.60
1	28	273	985	3812	18051
2	35	301	1090	5295	19032
3	47	482	1117	5824	21869
4	64	532	1185	6085	22861
5	72	574	1215	6367	23307
6	84	643	1310	7054	25628
7	98	702	1382	7162	26072
8	112	761	1402	7641	28590
9	127	810	1485	8020	32025
10	142	960	1540	8234	35570

4. PROBABILITY ANALYSIS OF FATIGUE TEST RESULTS

Since the fatigue lives showed larger scatter, an attempt to determine the probabilistic distributions was made. Few researchers [19, 20] have developed Weibull distribution models for fatigue lives at different stress levels in case of conventional concrete. In the present study lognormal distribution models were developed and verified for different stress levels.

4.1 Determination of Lognormal Distribution Model

The probability density function of lognormal distribution model is given by equation (1). The parameters of lognormal distributions are μ and σ which are mean and standard deviation of observed ln (N) values. In the equation (2), 'X' represents ln(N) values.

$$f_x(X) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(X-\mu)^2}{2\sigma^2}\right] \qquad \text{......... (1)}$$

The values lognormal distribution parameters at different stress levels are shown in table 5. The parameters of lognormal distribution were found to be dependent on the stress level.

Table 5: Lognormal Distribution Parameters for Fatigue Lives at Different Stress Levels

Stress level	Parameters of log normal distribution	
	μ	σ
0.80	4.271	0.548
0.75	6.334	0.411
0.70	7.138	0.145
0.65	8.765	0.232
0.60	10.118	0.215

4.2 Model Verification

The log normal models developed in the present investigation were tested using Kolmogorov-Smirnov test. For conducting this test, the test statistic D_2 was calculated using equation (2) in which F^O (N_j) is the observed distribution of N and F_N (N_j) is the hypothesized distribution of N and m is the total number of specimens.

$$D_2 = \max_{j=1}^{m}\left[\left|F^o(N_j) - F_N(N_j)\right|\right] \qquad \text{......... (2)}$$

The D_2 values were compared with critical D_2 for the given sample size and significance level of 5%. If calculated value is less than critical $D_{2,}$ model is accepted. The basic calculations for verification of lognormal model for PCC at stress level of 0.8 are shown in table 6. The D_2 values and verification of lognormal distributions at different stress levels are shown in table 7. It can be seen that lognormal model is acceptable at all stress levels.

Table 6: Kolmogorov-Smirnov test for lognormal distribution at stress level of 0.80

Nj	j	F^O(Nj) = j/m	F_N (N_j) from lognormal distribution	D_2 for lognormal distribution= | F^O (N_j)-F_N(N_j)|	Maximum D2 from lognormal distribution	D_2 for 5% significance level and m=10	Inference
14	1	0.1	0.1753	0.0753			Lognormal model for
17	2	0.2	0.2417	0.0417			
20	3	0.3	0.3471	0.0471			
24	4	0.4	0.4716	0.0716			

26	5	0.5	0.5206	0.0206	0.2236	0.41	fatigue life distribution is accepted
32	6	0.6	0.5841	0.0159			
32	7	0.7	0.6455	0.0545			
36	8	0.8	0.6958	0.1042			
39	9	0.9	0.7401	0.1599			
40	10	1	0.7764	0.2236			

Table 7: Kolmogorov-Smirnov test for lognormal distribution at different stress levels

Stress level	Maximum D2 from lognormal distribution	D_2 for 5% significance level and m=10	Inference
0.75	0.1366	0.41	Lognormal model for fatigue life distribution is accepted at all stress levels
0.70	0.0972	0.41	
0.65	0.1392	0.41	
0.60	0.1118	0.34	

5. DETERMINATION OF S-N RELATION

In the design of concrete pavements [1] the fatigue life at different stress levels due to different magnitudes of axle loading is predicted from the S-N relation. Hence S-N relation plays a vital role in the design of rigid pavements. In the current study S-N relation was developed by carrying out regression analysis on fatigue test data. The S-N curve determined for the composite high volume fly ash concrete is shown in figure 5. Also S-N curve determined by the authors for HFC [18] is shown in figure 5 along with that of composite section. S-N relations for composite and HFC sections along with the R^2 values are shown in equations (3) and (4) respectively, where R is the coefficient of correlation. The 95% confidence limits using constant variance were determined for the composite section. Upper and lower confidence limits along with S-N curve for composite section are shown in figure 6.

$$S = -0.034Ln(N) + 0.9493 \quad (R^2=0.9615) \quad \text{------------ (3)}$$

$$S = -0.0338Ln(N) + 0.9389 \quad (R^2=0.8759) \quad \text{------------ (4)}$$

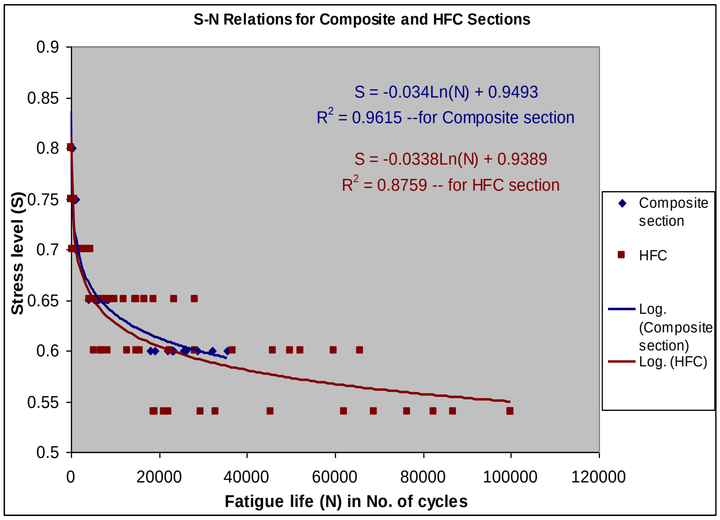

Figure 5: S-N Curves for Composite and HFC Sections

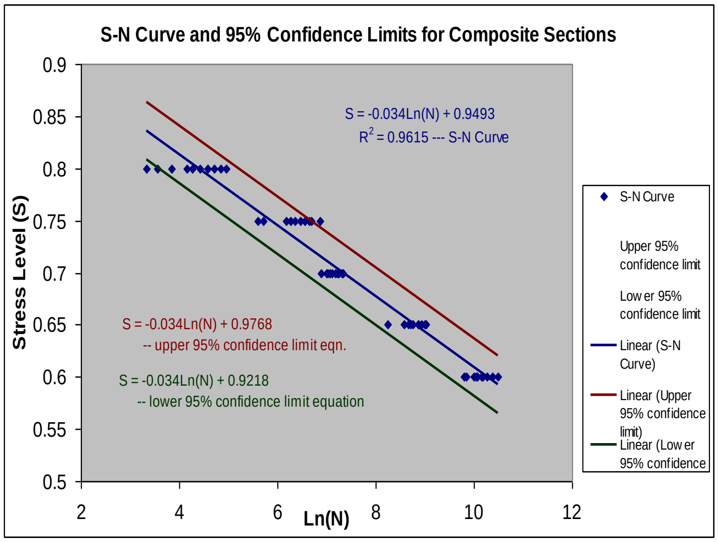

Figure 6: S-N Curve and 95% Confidence Limits for Composite Sections

6. DISCUSSION

The failure plain for all the composite specimens was lying in the flexural zone. Hence deep beam effect was not seen in any of the specimens. The bonding between HFC and DLHFC was perfect as indicated by both static and fatigue tests. The progress of crack did not stop at interface of pavement quality and lean concrete, instead whole beam cracked by the extension of single crack through the depth. The interface between the two concretes allowed stresses and strains to pass through it thus indicating possibility of stress concentration at the interface. Even though the phenomenon of failure of composite section by a single vertical crack i.e., reflection cracking raises apprehensions about usage of bonding between the two layers, the bond will be beneficial from the consideration of higher load carrying capacity and stiffer construction. To take into account higher load carrying capacity due to bond between the two layers it is important to concentrate on stresses in the bottom of the lean concrete rather than at interface. Also safety against thermal cracking of lean concrete sub base has to be ensured by providing expansion joints in the material at smaller spacing. Flexural fatigue behavior of composite section was better than the homogeneous section as indicated by the S-N curve. Fatigue life value of composite section was higher than the HFC especially at lower stress levels.

7. CONCLUSIONS

Based on experimental investigations following conclusions were made.

- Perfect bonding was exhibited between HFC and LHFC as indicated by static and fatigue tests. The bond can be obtained without any additional treatments
- For probability distribution of fatigue life of composite section lognormal distribution was found to be satisfactory.
- S-N relation was obtained for the composite section.
- Fatigue strength of composite section was higher than HFC section.
- From the criteria of higher load carrying capacity and much stiffer construction the bond between HFC and LHFC may be beneficial in design if rigid pavements.

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