FLEXURAL FATIGUE PERFORMANCE OF HYBRID FIBROUS SELF COMPACTING CONCRETE FOR BRIDGE DECKS

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ABSTRACT. This paper presents the results of an investigation conducted to analyse the flexural fatigue life of Hybrid Fibrous Self Compacted Concrete (HyFSCC) containing different proportions of steel fibres and polypropylene fibres. The Steel Fibres (SF) and Polypropylene Fibres (PPF) in the proportions of 75%SF-25%PPF, 50%SF-50%PPF and 25%SF-75%PPF by volume at total volume fraction of 1% were used. An experimental programme was planned to obtain the fatigue lives of HyFSCC, in which approximately 150 beam specimens of size 100 x 100 x 500 mm were tested under four point flexural fatigue loading. Approximately 54 compressive strength tests and 54 static flexural strength tests were also conducted to facilitate fatigue testing. The two parameter Weibull distribution has been used to describe the probability distributions of fatigue data of HyFSCC at different stress levels. The gradual replacement of steel fibres by the polypropylene fibres in the HyFRSCC mix has been found to significantly reduce the variability in the distribution of fatigue life of HyFRSCC.

Keywords: Fatigue strength, Hybrid fibre reinforced self compacted concrete, Weibull parameters

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INTRODUCTION

Self Compacting Concrete offers many benefits to the construction practice - the elimination of the compaction work results in reduced costs of placement, shortening of the construction time, reduction in noise during casting thus leading to better working conditions. Other advantages of SCC are - improved homogeneity of the concrete and the excellent surface quality without blowholes or other surface defects. The basic components of SCC are the same as used in Normally Vibrated Concrete (NVC). However, to obtain the required rheological properties of fresh SCC, a higher proportion of fine materials and the incorporation of chemical admixture, a super-plasticizer is necessary. Sometimes, a viscosity modifying agent may also be used for the stability of the mix [1]. The need for high powder content in SCC is usually met by using pozzolanic fillers like fly ash, silica fume, blast furnace slag and non pozzolanic fillers like limestone powder, chalk powder, dolomite fines and quartzite powder etc.

Many researchers, in the last decade, have started using fibres in SCC and as a result, Fibre Reinforced Self Compacting Concrete (FRSCC) is now being used in structures such as airport pavements, highway overlays, bridge decks and machine foundations. The fresh, mechanical properties under statically applied loads and durability characteristics FRSCC have been investigated [2, 3]. It has been observed that the performance of FRSCC was much better than that of NVFRC.

The fresh and hardened state properties of Hybridised Fibre Reinforced Self Compacting Concrete (HyFRSCC) have been tested by various researchers [4, 5, 6]. The positive results show that in well-designed hybrid composites, there is positive interaction between the fibres and the resulting hybrid performance may exceed that of mono fibre composites.

This study was planned to establish the probability distributions for HyFRSCC at different stress levels and to explore the beneficial effects of the replacement of steel fibres by polypropylene fibres on the variability in the distribution of fatigue life of HyFRSCC. It was also proposed to examine the flexural fatigue strength of HyFRSCC in terms of two-million cycles endurance limits so as to recommend the most suitable fibre combination for the optimum performance. Concrete incorporating different proportions of steel and polypropylene fibres at 25-75%, 50-50% and 75-25%, by volume at 1.0% fibre content was tested at stress levels ranging from 0.85 to 0.0.7 to obtain fatigue life data. The fatigue test data has been used to establish the probability distributions of HyFRSCC.

EXPERIMENTAL PROGRAMME

In the present study the Ordinary Portland Cement of 43 grade conforming to requirements of IS 8112-1989 has been used. Crushed stone aggregates (below 12.5 mm) of specific gravity 2.78 were used as coarse aggregates and locally available coarse sand of specific gravity 2.75 conforming to Zone II grain size distribution was used as fine aggregates. The water absorption of coarse aggregates was 0.28 % and that of fine aggregates was 0.25%. The Class F fly ash was used.

Glenium 51, a polycarboxylic ether based super-plasticizer as admixture was used in suitable dosages to obtain the required HyFRSCC mixes with different volume fractions of fibres.

Glenium Stream II was used as ViscosityModifying Agent (VMA). The following type of fibres in different combinations such as 75%-25%, 50%-50% and 25%-75% by volume shall be used at 1% volume fraction.

- Corrugated Steel Fibres (SF) of 1mm dia. and 30mm length and specific gravity of 7.8.
- Polypropylene Fibres (PPF) of 0.7mm dia and 10mm length and specific gravity of 0.91. (Figure 1)

Figure 1 Steel Fibres and Polypropylene Fibres used in HyFRSCC.

Suitable SCC mixes with different proportions of steel and polypropylene fibres were obtained through trials as per EFNARC guidelines [7]. The Mix Proportions of the mix are shown in Table 1.

Dosage of Super-plasticizer (SP) was kept in range of 0.6–1.2% by weight of cement content for various HyFRSCC mixes and dosage for Viscosity Modifying Agent (VMA) was kept between 0.35-0.5 percent of the cement content in order to meet required EFNARC limits for SCC. For compressive strength tests the specimens used were 150 x 150 x 150 mm cubes whereas standard prisms of size 100 x 100 x 500 mm were used for the static flexural strength tests.

Table 1 Mix Proportions of the SCC

Cement	Fly ash	Fine Aggregates	Coarse Aggregates	Water
410	205	846	602	277

Water/Binder ratio	Sand/Binder ratio	Coarse Aggregate/ Binder Ratio
0.45	1.37	0.98

The specimens were cast in the different batches. Each batch had fourteen flexural test specimen and six cubes for testing the 28-day compressive strength of each mix. The specimen for compressive strength tests were cured for 28 days, whereas, the specimens for flexural strength tests were cured for 90 days. The compressive strength tests were conducted on concrete cubes in a 200 tonnes Universal Testing Machine. The flexural strength and flexural fatigue of HyFRSCC was obtained by testing prism specimens under four point bending test. All the flexural strength tests were done on a 100 kN servo-controlled actuator. The fatigue tests were performed at different stress levels of 0.7, 0.75, 0.8 and 0.85 for the mixes with different fibre combinations.

The quality of each batch was tested by its compressive strength at 28 days. The compressive strength of HyFRSCC mix with 75%PPF-25%SF is 34.98MPa, for mix having 50%PPF-50%SF is 37.70 MPa and for 25% PPF-75%SF mix is 44.32 MPa. The specimens for flexural strength tests were cured for 90 days to avoid possible gain in strength during fatigue tests. The static flexural strength tests are prerequisite for estimating maximum and minimum load limits for flexural fatigue tests. The average static flexural strength was 6.28MPa, 6.90 MPa and 8.12 MPa for HyFRSCC mix having 75%PPF-25%SF, 50%PPF-50%SF and 25%PPF-5%SF, respectively. After the static flexural strength of a particular batch was established, the flexural fatigue tests were conducted. Constant-amplitude non-reversed flexural loads were applied at a frequency of 10 Hz. The fatigue test was terminated as and when the specimen failed or a maximum limit of 2 x 10^6 load cycles was reached (whichever was earlier). The fatigue life of each specimen at a particular stress level was recorded as number of cycles to failure (N). In total, 150 flexural fatigue tests and 54 complementary static flexural tests were conducted in this investigation. The result of flexural fatigue test in form of the no. of cycles to failure (N) for all the specimens tested at different stress levels (S) is shown in Table 2.

ANALYSIS OF FATIGUE LIFE OF HyFRSCC

A total number of 150 specimens were tested for flexural fatigue. But some fatigue test data points were considered for rejection as outliers. The Chauvenet's criterion for outliers was applied to the fatigue tests data and the points meeting this criterion were excluded from further analysis [8 – 11].

Probability Distributions of HyFRSCC

In the past, large safety factors were used in concrete structures design and the invariability in performance was not so important. The scatter in the fatigue life of fibre reinforced concrete is more as compared to that of plain concrete [12]. Hence the establishment of probability distributions of HyFRSCC at different stress levels is an important aspect.

It has been shown in earlier studies that the two-parameter Weibull distribution agrees well with the expected fatigue behaviour of engineering materials [13, 14]. Previously, log-normal distribution function had been used to describe the fatigue life data of concrete. Subsequently, it was shown that hazard function of the log-normal distribution decreases with time, which is contrary to the expected fatigue behaviour of engineering materials [15]. The distribution of fatigue life of plain concrete, Steel Fibre Reinforced Concrete (SFRC) and SFRSCC has been shown to approximately follow the two-parameter Weibull [11 – 14].

Table 2 Laboratory Fatigue Life Data (Number of Cycles to Failure N, in Ascending Order) for SCC and HyFRSCC

Stress Level 'S'	Fibre Mix Proportion		
	75% PPF - 25% SF	50% PPF - 50% SF	25% PPF - 75% SF
0.85	1328*	-	26752
	3381	7076	43624
	3685	11558	54609
	5745	15655	57112
	6716	15703	81883
	7369	17798	95616
	8259	22040	101279
	9350	20577	120751
	9662	22694	149535
	12526	30226	428627*
0.8	17151	34316	104081
	21022	46649	160975
	33768	72935	282617
	44226	96779	263783
	48844	109053	347265
	51036	138534	395725
	58378	150198	422670
	72993	175630	573945
	90163	188123	651842
	224587*	232589	833642
0.75	72292	115762	218071
	92328	228377	320087
	139221	220216	610927
	145828	366214	832488
	213822	460479	928548
	214795	608356	1001948
	300847	618858	1701461
	315474	721186	2000000**
	374036	1014342	-
	504842	1834568*	-
0.7	114197	174014	32080*
	182479	368955	199858
	378841	445067	431926
	428131	579904	852988
	553890	880284	1071948
	610136	925475	1269723
	702723	1351414	1912971
	851914	1452371	2000000**
	819860	1894242	-
	1324923	2000000**	-

* *Rejected as Outlier by Chauvenet's Criterion, not included in analysis.*

** *Specimen did not show any crack, test terminates at 2 million cycles, treated as run out, not included in analysis.*

Thus it is proposed to model the scatter or randomness in the fatigue life of HyFRSCC in this investigation by the two-parameter Weibull distribution. Firstly, the probability distributions of HyFRSCC have been obtained using graphical method and then the parameters of the Weibull distribution have been calculated by method of moments.

The cumulative distribution function $F_N(n)$ of Weibull distribution may be expressed by the following expression [16]

$$F_N(n) = 1 - \exp\left[-\left(\frac{n - n_0}{u - n_0}\right)^{\alpha}\right] \quad (1)$$

Where n is the specific value of random variable N; α is the shape parameter at stress level S; u is scale parameter at stress level S and n_0 is the minimum life at stress level S.
The survivorship function $L_R(n)$ is obtained from Eq.(1) as $1 - F_N(n)$ and may be expressed by the following expression

$$L_R(n) = \exp\left[-\left(\frac{n - n_0}{u - n_0}\right)^{\alpha}\right] \quad (2)$$

It is quite reasonable to assume the minimum life $n_0 = 0$ in fatigue studies. Equation (2) reduces to the following

$$L_R(n) = \exp\left[-\left(\frac{n}{u}\right)^{\alpha}\right] \quad (3)$$

Taking logarithms twice on both sides of the Eq. (3), the following expression is obtained

$$\ln\left[\ln\left(\frac{1}{L_R}\right)\right] = \alpha\ln(n) - \alpha\ln(u) \quad (4)$$

Equation (4) may be used to verify if the fatigue test data obtained from a series of experiments, at a particular stress level, fits the proposed two-parameter Weibull distribution. For this, a graph is plotted between $\ln[\ln(1/L_R)]$ and ln(n) and if the data falls approximately along a straight line, it indicates that the two-parameter Weibull distribution is a reasonable assumption for the analysis of fatigue life data. The parameters of the Weibull distribution α and u are obtained from the regression analysis. This method is known as the graphical method of analysis. In order to obtain a straight line graph for Equation (4), the fatigue test data, at a particular stress level, is arranged in ascending order of number of cycles to failure. The empirical survivorship function is calculated for each data point using the following expression [14, 16]

$$L_R = 1 - \frac{i}{k+1} \quad (5)$$

Where i = failure order number, and k = number of fatigue data points at a given stress level S. Figure 2 presents analysis of fatigue life data using Equation (4) at stress levels S = 0.85, 0.80, 0.75 and 0.70 for HyFRSCC containing 75%PPF-25%SF. The approximate straight line plots of the fatigue life at all the stress levels justify the validity of the two-parameter Weibull distribution. This is further substantiated by the values of the correlation coefficient which are 0.9895, 0.9934, 0.9883 and 0.9917 for fatigue life data at stress levels 0.85, 0.80, 0.75 and 0.70, respectively. The values of the correlation coefficient are also mentioned in the same figure. Similarly, Figures 3 and 4, show the analysis of the fatigue life data of HyFRSCC containing 50%SF-50%PPF and 25%PPF-75%SF respectively. The parameters α and u calculated directly from the analysis for the fatigue life of HyFRSCC corresponding to all the three proportions of steel and polypropylene fibres are listed in Table 3. The maximum value of shape parameter α as per this analysis is 2.4112 for mix having 75%PPF-25%SF and the least value of α as 1.1985 is observed in mix having 25%PPF-75%SF.

Table 3 Estimated Weibull Parameters for Fatigue Life Data by the Graphical Method

Stress Level 'S'	Parameter	Fibre Mix Proportion		
		75%PPF - 25%SF	50%PPF - 50%SF	25%PPF - 75%SF
0.85	α	2.4112	2.1563	1.9043
	u	8728	19497	98227
0.8	α	1.9075	1.6747	1.6091
	u	60743	153650	483140
0.75	α	1.6031	1.5465	1.3803
	u	291231	586309	1190296
0.7	α	1.5098	1.3736	1.1985
	u	690719	987710	1558900

Estimation of Parameters by the Method of Moments

In this method, the parameters are obtained by calculating the appropriate sample moments, such as sample mean and sample variance. The moments of the Weibull distribution may be written in the following form [16, 17]

$$E(n) = uT\left(\frac{1}{\alpha} + 1\right) \tag{6}$$

and

$$E(n^2) = (u)^2 T\left(\frac{2}{\alpha} + 1\right) \tag{7}$$

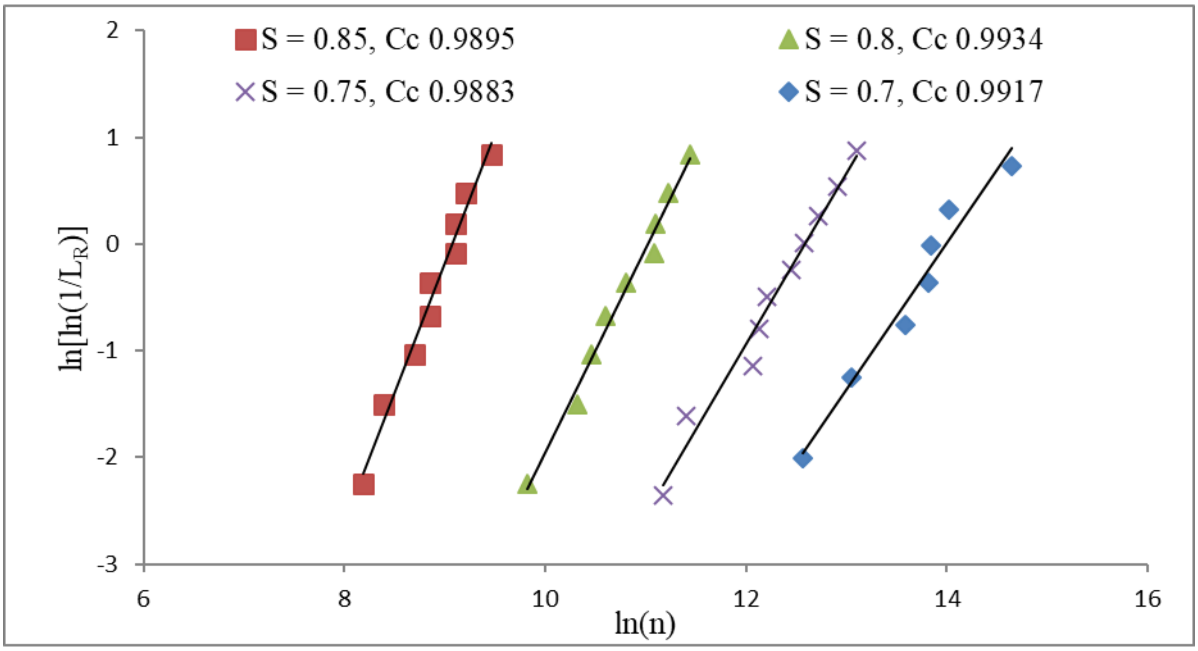

Figure 2 Analysis of Fatigue Life Data for HyFRCC (75%PPF-25%SF)

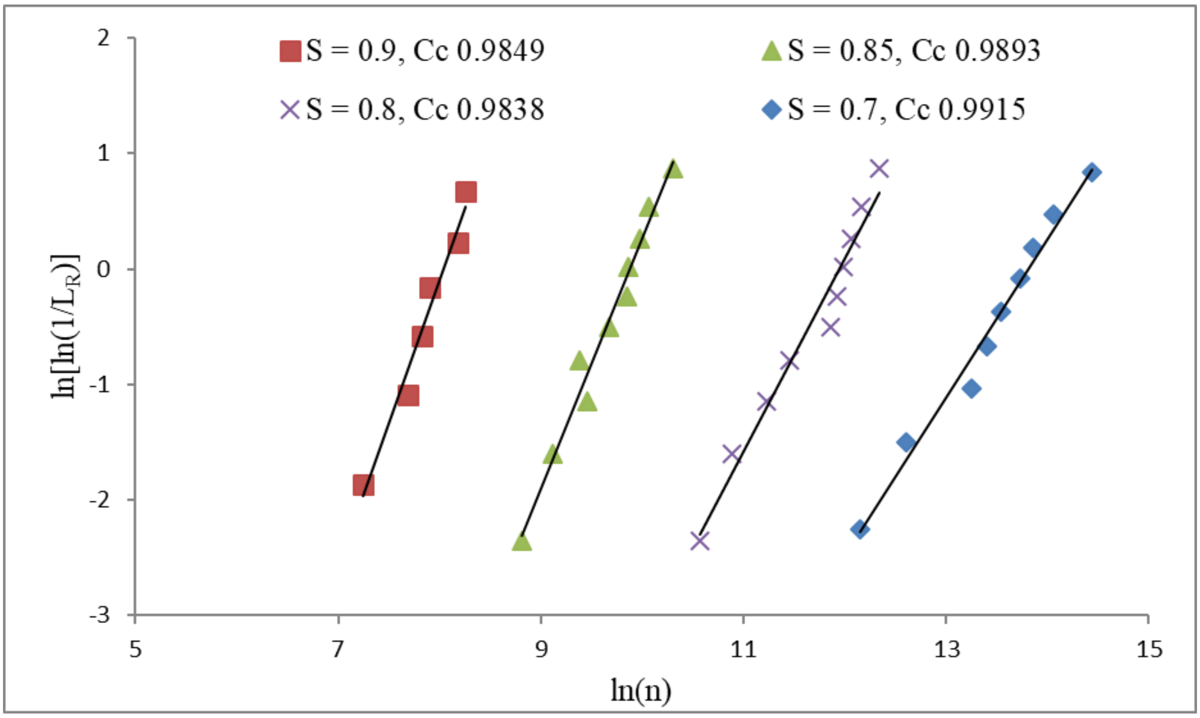

Figure 3 Analysis of Fatigue Life Data for HyFRCC (50%PPF-50%SF)

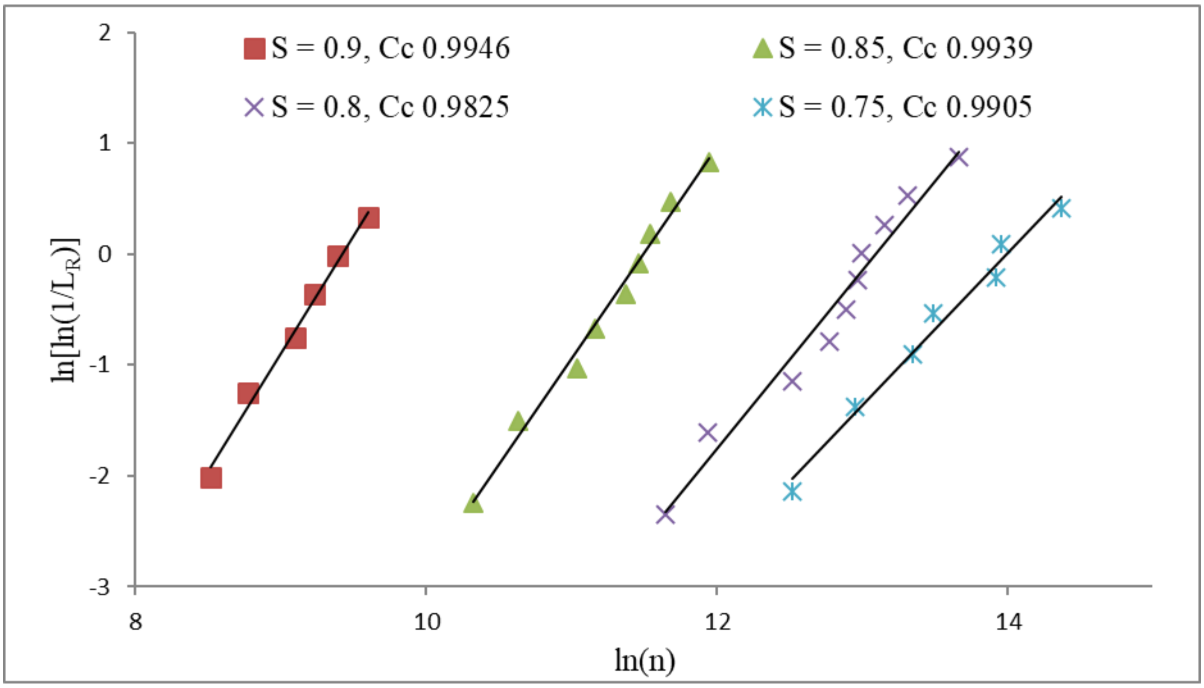

Figure 4 Analysis of Fatigue Life Data for HyFRCC (25%PPF-75%SF)

in which T( ) is gamma function and E( ) is expectation. Noting that the mean of the data sample under consideration at a given stress level S, $\mu = E(n)$ and the variance of the data sample at a given stress level S, $\sigma^2 = E(n^2) - \mu^2$, Equations (6) and (7) give the following expression

$$\left(\frac{\sigma}{\mu}\right)^2 = \frac{T\left(\frac{2}{\alpha}+1\right)}{T\left(\frac{1}{\alpha}+1\right)} - 1 \qquad (8)$$

in which $\frac{\sigma}{\mu}$ = CV is the coefficient of variation of the fatigue data sample at a particular stress level S and σ is the standard deviation. However, the following simpler expressions may be used to obtain the values of α and u [17]

$$\alpha = (CV)^{-1.08} \qquad (9)$$

$$u = \frac{\mu}{T\left(\frac{1}{\alpha}+1\right)} \qquad (10)$$

The parameters of the Weibull distribution for the fatigue life data of HyFRSCC containing different mix proportions of steel and polypropylene fibres were obtained by the method of moments using Equations (9) and (10) and are listed in Table 4.

Table 4 Estimated Weibull Parameters of the Fatigue Life Data by the Method of Moments

Stress Level 'S'	Parameter	Fibre Mix Proportion		
		75%PPF - 25%SF	50%PPF - 50%SF	25%PPF - 75%SF
0.85	α	2.8460	2.5516	2.3253
	u	8585	19077	95585
0.8	α	2.3213	2.2167	1.9963
	u	59149	147871	467437
0.75	α	1.9721	1.8212	1.7859
	u	281682	564938	970320
0.7	α	1.7592	1.7073	1.7287
	u	667498	943292	1200066

The beneficial effects of gradual replacement of steel fibres by polypropylene fibres in HyFRSCC can be seen in the way that, at a particular stress level, there is considerable reduction in the variability in the distribution of fatigue life of HyFRSCC by increasing the percentage of polypropylene fibres. This can be interpreted from the fact that the higher values of the shape parameter indicate lower variability in the distribution of fatigue life. The average value of Weibull parameters have been given in Table 5.

Table 5 Average value of Weibull Parameters for Fatigue Life Data

Stress Level 'S'	Parameter	Fibre Mix Proportion		
		75% PPF - 25%SF	50% PPF - 50%SF	25% PPF - 75%SF
0.85	α	2.6286	2.3540	2.1148
	u	8657	19287	96906
0.8	α	2.1144	1.9457	1.8027
	u	59946	150760	475289
0.75	α	1.7876	1.6839	1.5831
	u	286456	575624	1080308
0.7	α	1.6345	1.5404	1.4636
	u	679109	965501	1379483

The influence of increase in the polypropylene fibre content in HyFRSCC mix on the shape parameter is shown in Figure 5, wherein the shape parameter is plotted for different stress levels against percentage of polypropylene fibres in the concrete mix (i.e. 25%, 50% and 75%). The 0%PPF content in HyFRSCC mix represents 100% steel fibres i.e. SFRSCC.

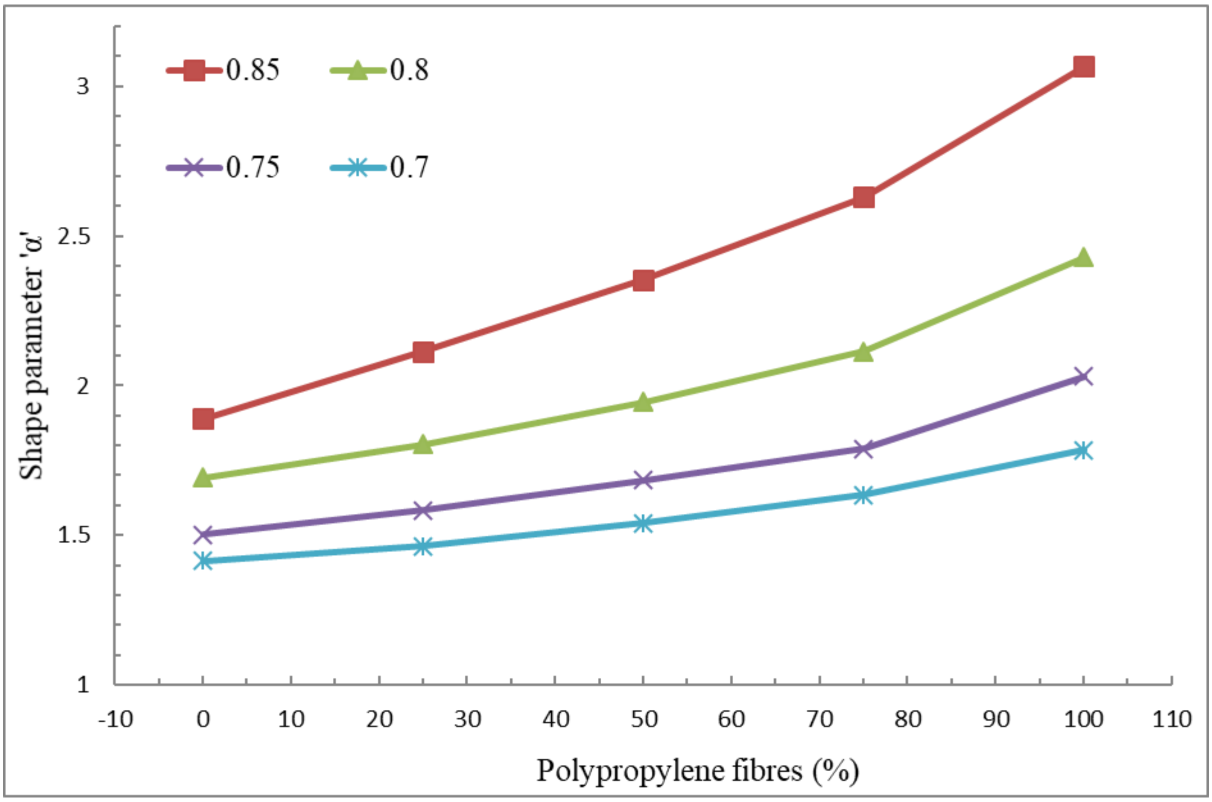

Figure 5 Effect of Addition of Polypropylene Fibres on Shape Parameter of HyFRSCC at Different Stress Levels

The effect of polypropylene fibre content in HyFRSCC on the shape parameter and coefficient of variation of fatigue test data at different stress levels has been quantified in Table 6. It can be seen from Table 6 that the increase in the values of the shape parameter at 0.85 stress level in HyFRSCC as compared to SFRSCC (100%SF) are 12%, 25% and 39% for 25%PPF-75%SF, 50%PPF-50% SF and 75%PPF-25%SF, respectively. Similarly, the decrease in the coefficient of variation of the fatigue test data at 0.85 stress level in HyFRSCC as compared to SFRSCC (100%SF) is 11%, 23% and 36% for 25%PPF-75%SF, 50%SF-50%PPF and 75%PPF-25%SF, respectively. The similar trends of increase in shape factor and decrease in coefficient of variation has been seen at stress level of 0.8, 0.75 and 0.7 by gradual replacement of SF with PPF. Thus through this investigation, the beneficial effects of subsequently replacing SF by PPF in terms of reduction in the variability in the fatigue test data of HyFRSCC have been established.

Moreover, for HyFRSCC the values of the shape parameters are higher at higher stress levels and vice versa thus indicating higher variability in the distribution of fatigue life of HyFRSCC at lower stress levels. It can be seen from Table 6 that the increase in the values of the shape parameter with 75% replacement of SF by the PPF in HyFRSCC is 39%, 25%, 19% and 16% at 0.85, 0.8, 0.75 and 0.7 stress levels respectively. Similarly, the decrease in the coefficient of variation of the fatigue test data with 75% replacement with PPF is 36%, 23%, 17% and 14% at 0.85, 0.8, 0.75 and 0.7 stress levels respectively. The same trends are true for other replacement levels also.

Table 6 Influence of Polypropylene Fibre Content on the Variability of Fatigue Life Data of HyFRSCC

Stress Level 'S'	Increase in Polypropylene Fibre Content in HyFRSCC (%)					
	Increase in Shape Parameter* (%)			Decrease in Coefficient of Variation of Test Data*(%)		
	0 to 25	0 to 50	0 to 75	0 to 25	0 to 50	0 to 75
0.85	12	25	39	11	23	36
0.8	6	15	25	6	14	23
0.75	5	12	19	5	11	17
0.70	3	9	16	3	8	14

**Calculated with reference to respective value at 0% polypropylene fibres i.e. SFRSCC.*

CONCLUSION

The flexural fatigue performance of HyFRSCC containing different proportions of polypropylene and steel fibres in the ratio of 25-75%, 50-50% and 75-25% by volume have been studied. It has been shown that the probability distributions of HyFRSCC at different stress levels can be modelled by the two-parameter Weibull distribution. Weibull Parameters of HyFRSCC have been obtained by graphical method and method of moments. Both the methods give almost similar values of the parameters. The gradual replacement of SF by the PPF in the HyFRSCC concrete mix has been proved to significantly reduce the variability in the distribution of fatigue life of HyFRSCC at different stress levels. A fibre mix combination of 75%PPF-25%SF has been found to be the most appropriate if only the reduction of variability in the fatigue life is the required criterion. Further, the mix with 25%PPF-75%SF has shown the maximum average static flexural strength of 8.12 MPa and the mix having 25%PPF-75%SF has the least average static flexural strength of 6.28 MPa.

REFERENCES

1. ACI COMMITTEE 237, Self Consolidating Concrete. ACI Emerging Technology Series, 237R-07, 2007, pp 1-30.

2. GRABOIS T M, CORDEIRO G C, FILHO R D T, Fresh and hardened-state properties of self-compacting lightweight concrete reinforced with steel fibers. Construction and Building Materials, 2016, Vol 104, pp 284–292.

3. SIDDIQUE R, KAUR G, KUNAL, Strength and permeation properties of self-compacting concrete containing fly ash and hooked steel fibres. Construction and Building Materials, 2016, Vol 103, pp 15–22.

4. HSIE M, TU C, SONG P S, Mechanical properties of polypropylene hybrid fibre-reinforced concrete. Material Science and Engineering, A 494, 2008, pp 153-157.

5. JAMERAN A, IBRAHIM I S, YAZAN S H, RAHIM S N A A, Mechanical properties of steel-polypropylene fibre reinforced concrete under elevated temperature. Procedia Engineering, 2015, Vol 125, pp 818 – 824.

6. MADANDOUST R, RANJBAR M M, GHAVIDEL R, SHAHABI S F, Assessment of factors influencing mechanical properties of steel fiber reinforced self-compacting concrete. Materials & Design, 2015, Vol 83, pp 284–294.

7. EFNARC, The european guidelines for self compacting concrete, specification, production and use. EFNARC, 2005, Vol 68.

8. JOHNSTON C D AND ZEMP R W, Flexural fatigue performance of steel fibre reinforced concrete - influence of fibre content, aspect ratio and type. ACI Material Journal, 1991,Vol 88, No 4, pp 374-383.

9. SINGH S P AND KAUSHIK S K, Flexural fatigue life distributions and failure probability of steel fibrous concrete. ACI Materials Journal, 2000, Vol 97, No 6, pp 658 - 667.

10. SINGH S P AND KAUSHIK S K, Flexural fatigue analysis of steel fibre-reinforced concrete. ACI Materials Journal, 2001, Vol 98, No 4, pp 306-312.

11. SINGH S P AND KAUSHIK S K, Fatigue strength of steel fibre reinforced concrete in flexure. Cement and Concrete Composites, 2003, Vol 25, No 7, pp 779-786.

12. GOEL S, SINGH S P, SINGH P, Flexural fatigue strength and failure probability of self compacting fibre reinforced concrete. Engineering Structures, 2012, Vol 40, pp 131-140.

13. ASTM 1963, A Guideline for Fatigue Testing and the Statistical Analysis of Fatigue Data. ASTM Special Technical Publication, 1963, 91-A.

14. OH B H, Fatigue analysis of plain concrete in flexural. Journal of Structural Engineering, ASCE, 1986, Vol 112, No 2, pp 273-288.

15. SHI X P, FWA T F AND TAN S A, Flexural fatigue strength of plain concrete. ACI Material Journal, 1993, Vol 90, No 5, pp 435–440.

16. OH B H, Fatigue life distributions of concrete for various stress levels. ACI Material Journal, 1991, Vol 88, No 2, pp 122-128.

17. WIRSCHING P H AND YAO J T P, Fatigue reliability: Introduction. Journal of Structural Division, ASCE, June 1982, pp 1201-1219.