Flexural Fatigue Strength of Reactive Powder Concrete under Repeated Cyclic Loading

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Abstract— RPC is an ultra-high strength and high ductility composite material with advanced mechanical properties. The high strength concrete fail under fatigue loads at load level below its static capacity. In the present study reactive Powder concrete with compressive strength of 165 MPa was produced. The hardened concrete is tested for compressive strength, flexural strength and flexural fatigue strength. An experimental investigation performed in which total 54 flexural fatigue tests and 15 static flexural tests are conducted on RPC specimens 100 x 100 x 500 mm in size containing steel fibre and polypropylene fibres separately. The results obtained from flexural fatigue tests are presented as S-N curve, with maximum fatigue stress expressed as a percentage of the strength under static loading and S-N relation is developed by carrying out regression analysis to determine fatigue life.

Key words: Flexural fatigue, Fatigue life, Reactive powder concrete (RPC)

I. INTRODUCTION

Most of the Structures such as deck slab of bridge, highway and airfield pavements are often exposed to repetitive (fluctuating) loads by moving traffic, which cause a structure to failure at a load level below its static capacity. Thus, fatigue loads (repeated loads) should be taken into consideration in the design of concrete structures [1].

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 [4]. 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 cyclic loads are applied for long times.

Reactive powder concrete (RPC) is a new type of concrete material. Compared with conventional concrete, RPC has ultra-high strength, high toughness and high durability. Combining the technical benefits and in-place costs, RPC was found to meet the prerequisites of value engineering particularly in airport, high way pavements and in bridge deck overlays. In the present paper, an attempt has been made to evaluate the fatigue behavior of the steel and polypropylene fibers reinforced RPC.

II. MATERIALS AND METHODOLOGY:

The constituents used in the RPC mixtures are different from the conventional concrete mixtures, which include ordinary Portland cement, silica fume, silica sand, quartz powder, super plasticizer, steel fibres, polypropylene fibres and water. Details of each constituent are tabulated in Table 1.

Sl.No.	Material	Specific gravity
1	Cement	3.15
2	Silica fume	2.2
3	Quartz Powder	2.6
4	Quartz sand	2.6
5	Super Plasticizer	1.1 to 1.2
6	Water	1

Table 1: Properties of Raw material

The short straight steel fibres are used of 12 mm length and 0.2 mm diameter. The steel fibre is generally 2% of the volume of concrete. The polypropylene fibres are used of 13 mm length and 0.2 mm diameter. The polypropylene fibres used in RPC about 0.2% to 0.35% by weight of cement are tabulated in table 2.

III. MIXING AND CASTING OF CONCRETE

Dry mixing powders (including cement, silica fume, quartz powder and silica sand) for about 3 minutes with a low speed of about 140 rpm. Addition of sixty percentage volume of water containing half amount of superplasticizer, and mix for about 3 minutes with a higher speed of about 285 rpm. Add the remaining water and superplasticizer, and mixed for about 10 minutes with a higher speed of about 285 rpm.

IV. METHODOLOGY

In the present study the mix design obtained using mix design procedure of high performance concrete given by P.C.Aitcin [17. An experimental investigation performed in which total 54 flexural fatigue tests and 15 static flexural tests are conducted on RPC specimens 100 x 100 x 500 mm in size containing steel fibre and polypropylene fibres separately

	Name of fiber used	
	Steel fiber	Polypropylene fibers
Control RPC	-	-
RPCS	2% by volume of concrete	-
RPCPP1	-	0.2% by weight of cement
RPCPP2	-	0.275% by weight of cement
RPCPP3	-	0.35% by weight of cement

Table 2: Percentage of fibres used in RPC

The flexure fatigue tests as well as static flexure tests were conducted on the actuator testing machine. The beams were simply supported on an effective span and loaded at third points as shown in the Figure 1. The span points of loading in the fatigue tests were kept the same as for the static tests. The flexure fatigue tests were loading by load controlled mode. Flexural fatigue tests were conducted at different stress levels (S) and stress ratio (R) is defined. Constant-amplitude sinusoidal loads were applied at a certain frequency. The numbers of cycles to failure for each specimen under different stress levels were noted as fatigue-life N. The S-N diagram plotted nominal stress level S versus cycles to failure N.

Fig. 1: Testing of beam prism

V. Results and Discussions

A. *Compressive Strength:*

Standard 100×100×100 mm cubes were tested to find 28 days compressive strength in accordance with IS 516-1959 using servo controlled compression testing machine of 3000 kN capacity. The Figure 2 shows the testing facility. The values of compressive strengths obtained are tabulated in Table 3. The results demonstrate that the RPCS containing steel fibre show better compressive strength than the control RPC concrete and RPC containing polypropylene fibres. From the results it observed that the addition of the polypropylene fibre in the control RPC mix has a little effect on the compressive strength. The use of polypropylene fibres increases the compressive strength of concrete when the polypropylene fibre is 0.2% and then reduction in compressive strength is observed.

Fig. 2: Testing of Concrete Cube

Specimen	**Compressive strength of concrete (MPa)**			**Average Compressive strength of concrete (MPa)**
Control RPC	110	119	116	115
RPCS	164.4	169.9	161.8	165.367
RPCPP1	138.6	145.4	141.2	141.8
RPCPP2	132.1	128.6	129.9	130.2
RPCPP3	121.6	123.8	120.4	121.94

Table 3: Average compressive strength test results

B. *Static Flexural Strength:*

To obtain the maximum and the minimum load limits for the fatigue tests, it was obligatory to estimate the static flexural strength of concrete mixes. Standard 100×100×500 mm beam specimens were tested for static flexural strength under two-point loading arrangement using a 500 kN closed-loop servo-controlled actuator.

Specimen	Static Flexural Strength (MPa)			Average Static Flexural Strength (MPa)
Control RPC	9.38	9.75	10.2	9.78
RPCS	12.77	12.68	13.2	12.89
RPCPP1	10.75	10.52	10.96	10.75
RPCPP2	11.66	11.68	11.83	11.72
RPCPP3	12.15	12.8	12.10	12.35

Table 4: Average static flexural strength test results

Three specimens from a particular batch of concrete were tested and maximum load was noted from the load-deflection curve. The rest of the specimens from a particular batch of concrete were tested in flexural fatigue with the maximum and minimum loads in fatigue tests being determined from the static flexural strength so obtained. The Static flexural strength test results for the mixes under study are presented in Table 4.

The average static flexural strengths of RPC with 0.2%, 0.275% and 0.35% of polypropylene fibres by volume fraction were obtained as 10.75, 11.72 and 12.35 MPa respectively. The static flexural strength of control RPC was 9.38 MPa. Increasing the polypropylene fibre content from 0.2% to 0.35% had significant beneficial effect on the static flexural strength of RPC concrete. There was an increase of 13.98%, 24.95% and 31.67% in the static flexural strength of RPCPP over the control RPC concrete with the addition of 0.2%, 0.275% and 0.35% of polypropylene fibres to concrete respectively. The average static flexural strength of RPCS was 12.35 MPa and increased about 37.43% over the Control RPC.

C. *Flexural Fatigue Analysis of RPCS:*

After the static flexural strength of a particular batch was set up, remaining specimens from the same batch were tested in flexural fatigue. The fatigue parameters include static flexural strength, stress level, stress ratio and loading frequency. The load cycle characteristic value or stress ratio 'R' is expressed as R= f_{min}/f_{max}, where f_{min} and f_{max} refer to the minimum and maximum fatigue stress. The stress level 'S' is expressed as f_{max}/f_r, where f_r is the static flexural strength. The fatigue tests were performed with stress level ranging from 0.9 to 0.3 and at constant stress ratio value of

0.1 for RPCS. The test was carried out in load control mode using a continuous sinusoidal waveform with a loading frequency of 2 Hz. According to M K Lee et al [4] fatigue life from 1000 to 200000 cycles is considered for design of airport pavements, bridges and railway bridges. Hence in this study, fatigue limit is defined as when the testing specimen fails or two lakh cycles limit reached without failure. Fatigue test results of the RPCS concrete are tabulated in Table 5

Stress levels	No. of cycles (N)		
	Beam1	Beam2	Beam3
0.3	200000	200000	200000
0.4	200000	200000	200000
0.5	154089	200000	200000
0.7	32854	26051	18543
0.8	2986	3078	3486
0.9	689	749	749

Table 5: Fatigue Life data under constant amplitude loading

S-N relations were developed by carrying out regression analysis on fatigue test data of RPCS under constant amplitude loading. The scatter diagram and the logarithmic relationship obtained are shown in Figure 3.

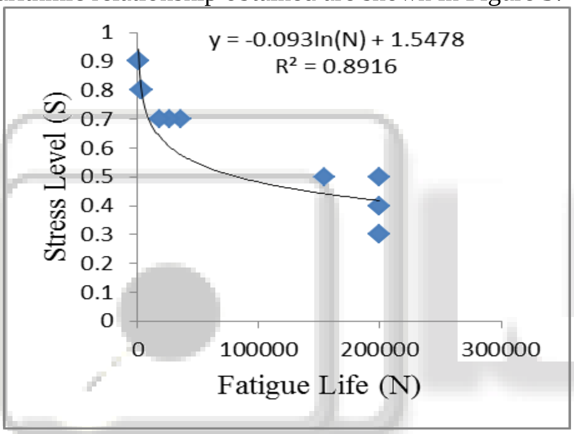

Fig. 3: Relationship between stress level and fatigue Life

It is observed that at the higher stress amplitude the concrete specimens sustained fewer cycles to failure and as stress amplitude reduced the number of cycles to failure also increased gradually. The regression equation (Eq.1) generated from the S-N curve can be used to estimate fatigue cycles at various stress amplitudes. The predicted range of two lakh cycles limits of load application for RPCS is 41.26% of static flexure strength.

$$S = -0.093\ln(N) + 1.5478 \quad (R^2 = 0.8916) \qquad (1)$$

D. Fatigue Analysis of Control RPC Incorporating Polypropylene Fibers:

The fatigue tests were performed with stress level ranging from 0.7 to 0.9 with same procedure as followed for RPCS incorporating steel fiber. The fatigue life data of the tested beam specimens for control RPC and RPC incorporating polypropylene mixes is shown in Table 6. Individual “Stress level versus number of Cycles” curves were created based on 3 replicates in each stress level for control RPC and 0.2 %, 0.275 %, and 0.35 % polypropylene fibres reinforced RPC.

Designation	Stress Level/ Sl.no	0.7	0.8	0.9
Control RPC	1	10505	1092	454
	2	16271	2158	498
	3	17407	2431	589
RPCPP1	1	12546	1056	378
	2	16261	2541	493
	3	19246	2643	523
RPCPP2	1	7058	1680	341
	2	17261	2685	524
	3	18244	2864	587
RPCPP3	1	15482	2861	495
	2	16231	3148	598
	3	19264	3461	637

Table 6: Fatigue Life data under constant amplitude loading

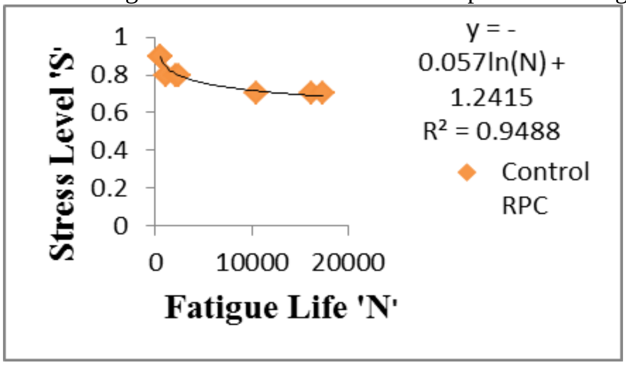

Fig. 4: Fatigue life at different stress Level

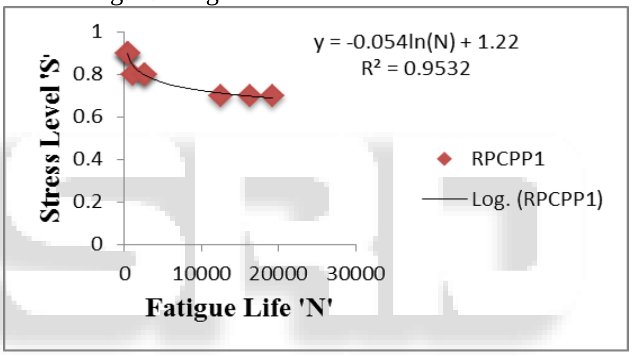

Fig. 5: Fatigue life at different stress Level

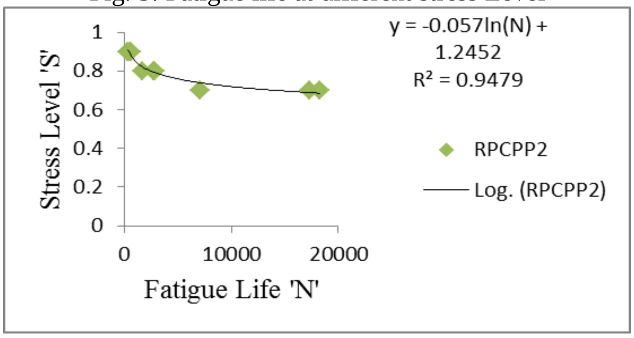

Fig. 6: Fatigue life at different stress Level

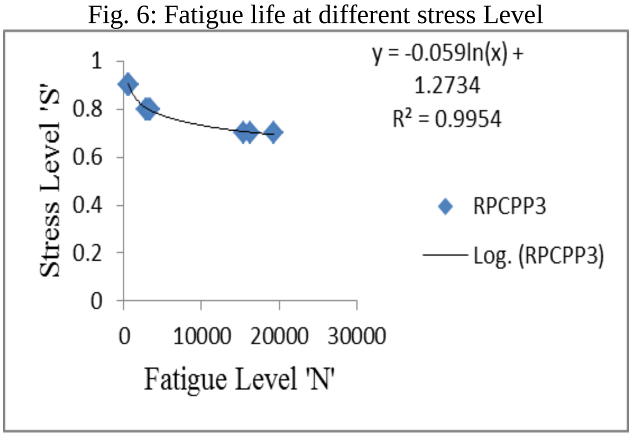

Fig. 7: Fatigue life at different stress Level

Figures 4, 5, 6 and 7 present the *S-N* relationships for control RPC and RPC with different volume fractions of polypropylene fibres. Increasing the fibre content from 0.2 to 0.35% improves the fatigue performance significantly. S-N relations for control RPC, RPCPP1, RPCPP2 and RPCPP3 are shown in below with R^2 values where R is the coefficient of correlation.

$S = -0.057\ln(N) + 1.241 \quad (R^2 = 0.9488) \quad (2)$
$S = -0.054\ln(N) + 1.22 \quad (R^2=0.9532) \quad (3)$
$S = -0.057\ln(N) + 1.2452 \quad (R^2 = 0.9479) \quad (4)$
$S = -0.059\ln(N) + 1.2734 \quad (R^2 = 0.9954) \quad (5)$

VI. Conclusion

From the experimental results presented in this study, the following conclusions can be drawn:

(1) The maximum compressive strength of RPC with steel fibre 165.367 MPa is achieved with cement content of 900 kg/m^3 with water binder ratio of 0.18 by incorporating 2% steel fibre.
(2) Results indicated that, by increasing the volume fraction of polypropylene fibres from 0% to 0.2%, 0.275%, and 0.35% the cube compressive strength was increased by 16.20%, 10.71%, and 5.34% respectively
(3) Flexure strength of RPC containing steel fibre increased about 37.43% in comparison with control RPC.
(4) Increasing the volume fraction of polypropylene fibres from 0% to 0.2%, 0.275%, and 0.35% resulted in an increase in the flexure strength by 13.98%, 24.95%, and 31.67% respectively.
(5) The linear relation between stress level (S) and number of cycles (N) for control RPC, RPCS, RPCPP1, RPCPP2 and RPCPP3 are developed with co-efficient of co-relation R^2 are shown below. The high R^2 value indicates good correlation for the linear relationship between the parameters of the present studies.

$S = -0.057\ln(N) + 1.241 \quad (R^2 = 0.9488)$
$S = -0.093\ln(N) + 1.5478 \quad (R^2 = 0.8916)$
$S = -0.054\ln(N) + 1.22 \quad (R^2=0.9532)$
$S = -0.057\ln(N) + 1.2452 \quad (R^2 = 0.9479)$
$S = -0.059\ln(N) + 1.2734 \quad (R^2 = 0.9954)$

(6) Increasing the polypropylene fibre content from 0.2 to 0.35% improves the fatigue performance significantly.
(7) The numbers of cycles increases as stress level decreases for RPCS and RPCPP beams.

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