FAILURE PROBABILITY OF CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATES UNDER FLEXURAL FATIGUE

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ABSTRACT. The paper presents results of an investigation conducted to assess the probability of fatigue failure of concrete in which the Coarse Natural Aggregates (NA) were replaced with Coarse Recycled Concrete Aggregates (RCA). Concrete mix containing 100% NA was also tested for comparison purpose. The fatigue test data of concrete made with 100% RCA and 100% NA was obtained by conducting flexural fatigue tests on beam specimens of 100x100x500 mm size. Static flexural tests were also conducted to facilitate fatigue testing. To predict the flexural fatigue strength of concrete made with RCA, the materials coefficients of fatigue strength prediction models have been obtained. The S–N–Pf curves have been generated from the fatigue test data for concrete made with RCA. Two-Million cycles fatigue strength has also been estimated for concrete mixes containing 100% RCA and compared with that of concrete made with 100% NA.

Keywords: Coarse Recycled Concrete Aggregates (RCA), Coarse Natural Aggregates (NA), Fatigue, Probability of Failure, Two-Million Cycles Fatigue Strength.

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INTRODUCTION

The concept of sustainable development includes, first and foremost, the judicious use of rapidly depleting natural resources, achieved by using industrial by-products and thereby reducing materials waste [1]. According to Eurostat the total amount of waste generated in the European Union, in 2010, was over 2.5 billion tonnes, of which almost 860 million tonnes belonged to construction and demolition (C & D) activities [2]. India produces 23.75 million tonnes of construction and demolition waste annually. The dumping of this C& D waste is becoming an environmental issue due to limited land space availability. Simultaneously the natural resources are depleting even on a faster rate as the construction industry is believed to be the biggest consumer of the natural resources, which are already very scarce [3]. Therefore the best way possible to counterbalance the excessive use of natural resources in production of concrete is the utilization of processed C & D waste in construction industry. The waste generated from the demolished structures like old pavements and high rise structures is collected and recycled aggregates are obtained by crushing the waste to the required sizes thus making the construction more sustainable [4-6].

In order to conserve the natural aggregates and make the construction more environment friendly, the concrete aggregates obtained from demolished buildings can be a substitute to natural aggregates in structural concrete. There are different types of Recycled Aggregates (RA) such as concrete aggregates, glass cullets, brick masonry aggregates, asphalt and bitumen, ceramic tiles leftovers, etc. Among various RA available, the one obtained by demolition of parent concrete structures are typically referred to as recycled concrete aggregates. Recycled concrete aggregates offer many technical benefits i.e. processed form of recycled concrete aggregates can be applied for making structural concrete, landscape works, wall backfills, laying of pavements and so on.

From past five or six decades a considerable research has been carried out on the properties of coarse and fine recycled concrete aggregates meticulously on coarse recycled concrete aggregates (RCA) and their use in structural concrete. The Coarse Recycled Concrete Aggregates normally consists of the Coarse Natural Aggregates (NA) surrounded by a layer of adhered mortar of source concrete. This attached mortar strongly affects the physical and mechanical properties of RCA. When compared to NA, the density of RCA is generally lower as the density of adhered mortar is less than the underlying rocks [4]. As reported earlier, there is about 17% difference between the bulk densities of RCA and NA, with values of 2394 kg/m^3 and 2890 kg/m^3 respectively. Some authors have reported the density of RCA to be 7–9% lower than that of NA [7, 8].

Coarse recycled concrete aggregates have high porosity due to the adhered mortar on the surface of RCA and their high porous nature leads to an increase in the water absorption capacity. The water absorption capacity usually ranges up to 12% for RCA [9]. Coarse Recycled Concrete Aggregates have high crushing and impact value than NA. The characteristics and the amount of RCA in concrete can influence the strength properties of concrete. All the mechanical properties i.e. static compressive strength, static flexural strength and splitting tensile strength are affected due to the presence of residual mortar on RCA. The concrete made with RCA shows up to 30% loss in compressive strength for 100% replacement of NA with RCA [10, 11]. However, to obtain the same compressive strength with 50–100% replacement of NA with RCA, w/c ratio needs to be lowered by 4–10% [12].

A similar behavior in splitting tensile strength has been observed in concrete made with RCA as in case of compressive strength. However, the splitting tensile strength is slightly affected with the content of RCA in concrete. Some investigations indicated that concrete made with RCA either shows comparable or superior split tensile strength than that of concrete made with NA [13, 14]. This enhanced performance in tensile strength is attributed to the increased absorption by adhered mortar layer on recycled aggregates as well as an effective ITZ, consequently improving the bond between aggregates and the mortar matrix [12]. The flexural strength of concrete made with RCA has also been found to decrease with increase in the quantity of RCA. A decrease of about 10% in the flexural strength has been reported [15-17]. By taking into consideration the previous studies it is generally said that the majority of the research on concrete containing RCA has been focussed on mechanical and durability properties of hardened concrete matrix and rheological properties of fresh concrete made out of RCA. Owing to various technical and economical benefits of RCA, the application of RCA concrete can be in making bridges, dams, road pavements and precast structural elements. But most of the structures above are influenced by fatigue loading, thus there exists a need of testing the RCA concrete under fatigue loading.

An extensive literature is available on fatigue properties of concrete made with NA. The fatigue performance of concrete has been checked by estimating the various characteristics such as S-N relationship, endurance limit, design fatigue life, Weibull distribution parameters (shape parameter and scale parameter), and theoretic fatigue life and so on. Various fatigue models have also been analysed to check the fatigue strength of concrete containing NA. It has been well concluded that the span of stress levels influences the fatigue strength of concrete considerably. Generally, with the increase in the stress value the fatigue strength decreases [18-21]. In spite of this, a few studies exist on the fatigue properties of concrete containing RCA. The concrete mad with RCA shows lesser value of endurance limit in comparison to the concrete made with NA similar to the case of compressive strength [22, 23]. It is well known that the fatigue phenomenon has a statistical nature due to which a large variability occurs in the fatigue life data of concrete at a considered stress level. Therefore, a large number of specimens should be required to apply the probabilistic analysis to get statistically significant fatigue data. This approach has been adopted by previous investigators[19, 20] in their fatigue studies on concrete made with NA.

Since limited studies on fatigue behaviour of concrete containing RCA are available, therefore by keeping in view the ample potential of RCA, the following research study has been carried out to determine the fatigue performance of concrete containing 100% RCA as replacement of NA. A concrete mix containing 100% NA has also been made for the comparison purpose. RCA for possible practical applications by comparing the results obtained with that of NA used in the present work.

RESEARCH SIGNIFICANCE

A succinct review of literature has been given in the preceding section which shows that though a tremendous amount of work has been carried out on the concrete made with RCA to investigate its mechanical properties under statically applied loads, yet the information about the dynamic (fatigue) behaviour of concrete made with RCA is meagre. The fatigue performance is a critical parameter to design a concrete structure which is of a structural importance. Therefore a present investigation was planned to examine the fatigue performance of concrete made with RCA in which S-N and S-N-P_f relationships were proposed to be examined which are used for concretes made with NA in the present as well as in previous studies[19-21]. Two million fatigue strength has been calculated and compared with that of concrete made with NA. It is anticipated that the results of this investigation, which forms part of a larger investigation currently in progress, will provide design engineers with greater confidence when using concrete made with RCA in structures that are most commonly influenced by fatigue loads.

EXPERIMENTAL PROGRAMME

A total of 64 flexural fatigue tests and 48 complementary static flexural tests were executed on beam specimens of size 100mm × 100mm × 500mm under four point flexural loading. A total of 48 compressive strength tests were also conducted on different batches of concrete to check the quality of each batch after 28 days of curing.

Mix Proportions and Materials Used

In the present investigation two concrete mixes were cast based on the percentage replacement of NA with RCA. First concrete mix is made with 100% NA and other concrete mix was made up of 100% RCA. Well graded RCA of size 12.5 mm (maximum) with a specific gravity of 2.46 and crushing value of 25.6% were obtained from the demolished concrete specimens available in the concrete laboratory of the authors' institute. Natural Aggregates of same size were obtained from the local market. The grading curve of NA and RCA used in the study is given in Figure 1. The grading of the RCA was deliberately kept similar to that of NA. Ordinary Portland cement (OPC) of 43 grade was used in the investigation. Locally available coarse sand was used as fine aggregates in this study. A stipulated doze of superplasticizer was used to get a workable concrete mix. The mix proportion used in the current investigation is given in Table 1.

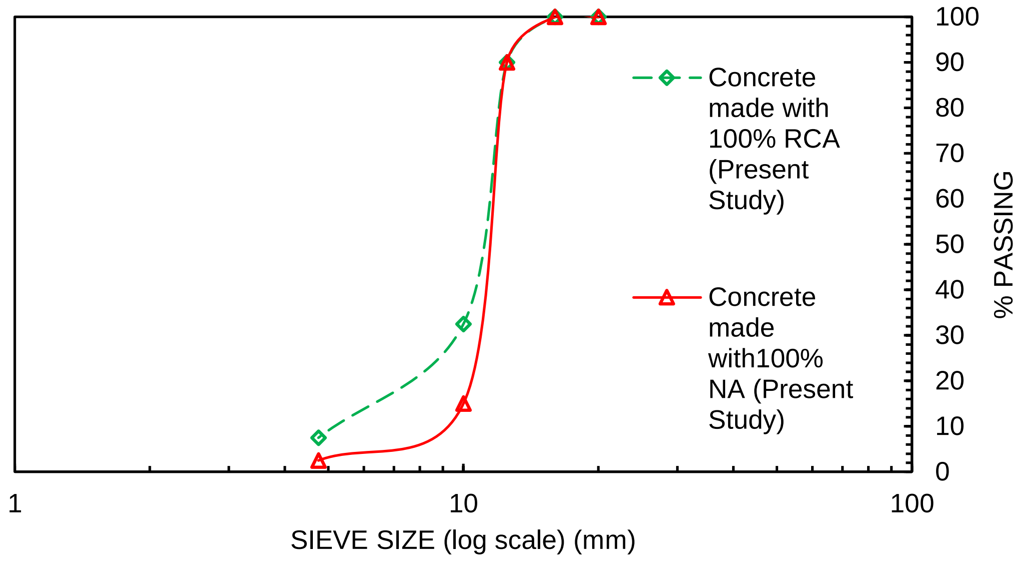

Figure 1 Grading curves for RCA and NA used in present study

Casting and Testing of Specimens

In this investigation, concrete specimens were cast in batches wherein each batch consists of 3 cube specimens of size 150mm × 150mm × 150mm and 7 beam specimens of size 100mm × 100mm × 500mm. The cube specimens were made to investigate the compressive strength of concrete whereas beam specimens were cast to investigate static flexure and flexural fatigue of concrete mixes. Slump tests were performed to check the workability of all the concrete mixes and the observed slump was in a range of 60mm to 90mm. The compressive strength tests were conducted at a curing age of 28 days. The curing of beam specimens was carried out for 90 days and thereafter kept in laboratory conditions for more than 2 months to avoid any possible enhancement in strength during fatigue testing. Out of 7 beam specimens, generally 3 specimens were tested under static flexure. This was done to calculate the minimum and maximum loads to perform fatigue tests on the remaining 4 beam specimens of a particular batch.

All the static flexural strength and flexural fatigue tests were conducted on a 100 kN MTS servo-controlled actuator. The fatigue loads were applied in the form of sinusoidal loads with constant amplitude at a loading frequency of 10 Hz at different stress levels ($S = f_{max}/f_r$; f_{max} = maximum fatigue stress and f_r = static flexural strength) ranging from 0·85 to 0·65 at a constant stress ratio ($R=f_{min}/ f_{max}$; f_{min} = minimum fatigue stress) of 0·10. An endurance limit of two million cycles of fatigue load was fixed to save time and expense, because of the large number of specimens to be tested. The test was terminated as and when specimen failure took place or the upper limit was reached, whichever was earlier. The average static compressive strength and average static flexural strength of RCA-100 and RCA-0 were observed to be 31.70 MPa & 4.53 MPa and 41.77 MPa & 5.10 MPa respectively. The batch-wise comparative representation of average static flexural strength and average static compressive strength is given in Table 2.

Table 1 Mix proportions for different concrete mixes per m^3

MIX DESIGNATION	BINDER		FNA (KG)	RCA (KG)	NA (KG)	WATER (LITERS)
	OPC (Kg)	FA (Kg)				
RCA-0	343	148	762	----	1003	206
RCA-100	343	148	762	935	----	206

w/b = 0.42; water/cement = 0.60; *(binder = OPC + FA)*

Table 2 Average static flexural strength and average static compressive strength test results of different concrete mixes

BATCH NO.	STATIC FLEXURAL STRENGTH (MPa)		STATIC COMPRESSIVE STRENGTH (MPa)	
	RCA-0	RCA-100	RCA-0	RCA-100
1	5.95	4.59	35.40	30.24
2	4.90	4.84	40.70	32.09
3	5.29	4.17	36.83	34.52
4	4.45	4.89	46.24	32.87
5	4.89	4.66	41.54	31.66
6	5.22	4.29#	44.38	31.10
7	5.05	3.98	47.62	30.56
8	5.02	4.79	41.44	30.47
Average	5.10	4.53	41.77	31.70

#Average of two specimens, without mark (#) Average of three specimens

FLEXURAL FATIGUE TEST RESULTS AND ANALYSIS

The fatigue test data obtained for concrete mixes RCA-100 and RCA-0 at different stress levels in this investigation is tabulated in Table 3. Data points meeting the criterion for rejection as outliers were identified using Chauvenet's criterion, and these were rejected and excluded from further analysis [24].

S-N Models for the Prediction of Fatigue Strength

These fatigue models have been used in the previous research studies [20, 21] to evaluate the fatigue strength of the concrete made with NA. Therefore it is intended to calculate the material coefficients of these fatigue models as they can be used to investigate the fatigue strength of concrete made with RCA (i.e. RCA-100).

Table 3 Fatigue life data (number of cycles to failure, *N*) for concrete mixes RCA-0 and RCA-100

Stress Level (S)	0.85	0.75	0.65
RCA-0	444[a]	10781	100801
	1137	13879	142054
	1367	18489	187623
	1678	21945	220075
	1945	25467	260685
	2271	31256	323068
	2605	36543	360845
	2647	42842	456944
	3096	46951	512089
	3987	51348	558973
RCA-100	567	192[a]	67225
	789	4353	68738
	1054	5615	88969
	1188	9382	90371
	1345	9792	120805
	1765	12829	189763
	1897	13702	249867
	2098	14045	261009
	2156	23020	319551
	2354	26079	409876

[a]Rejected as Outlier by Chauvenet's Criterion, not included in Analysis

First S-N relationship popularly known as Wholer's equation is given as under:

$$S = \frac{f_{max}}{f_r} = A_1 + A_2 log10(N) \tag{1}$$

where, f_{max}/f_r is Stress Ratio and A_1&A_2 are the experimental coefficients.

The second S-N relationship is called the modified form of Wholer's equation [20, 25] is given as under:

$$S = \frac{f_{max}}{f_r} = 1 - \beta(1 - R)log_{10}(N) \tag{2}$$

where, β is a material coefficient. The R term is incorporated to simulate the loading conditions in actual structures where the minimum value of repeated stress is not zero.

The third form of fatigue equation is a power formula [26] written as

$$S = \frac{f_{max}}{f_r} = C(N)^{-D} \tag{3}$$

where, C and D are the experimental coefficients. The distinctive feature of eq. (3) is that the value of N increases as S becomes small. This equation satisfies the extreme boundary condition by having N approaching infinity as S approaches zero.

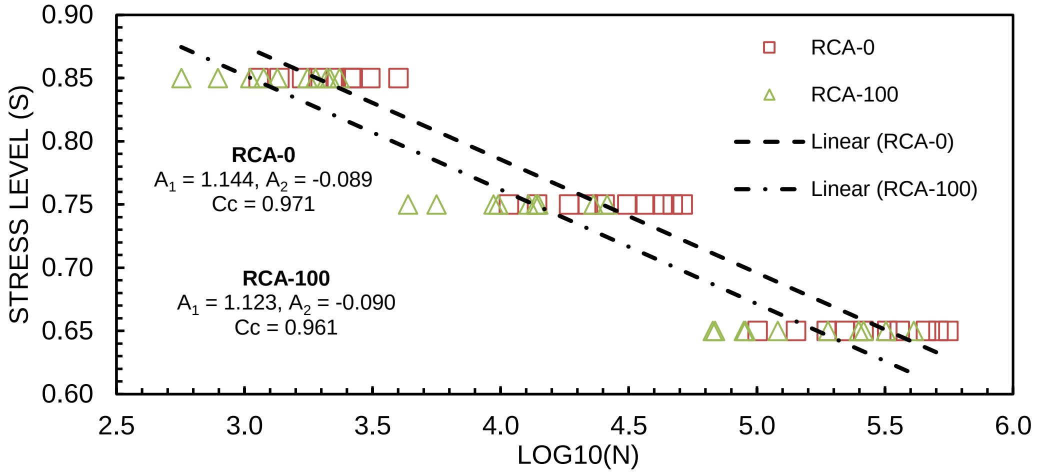

Figure 2 Estimation of coefficients A_1 and A_2 of eq. (1) for concrete mixes RCA-0 and RCA-100

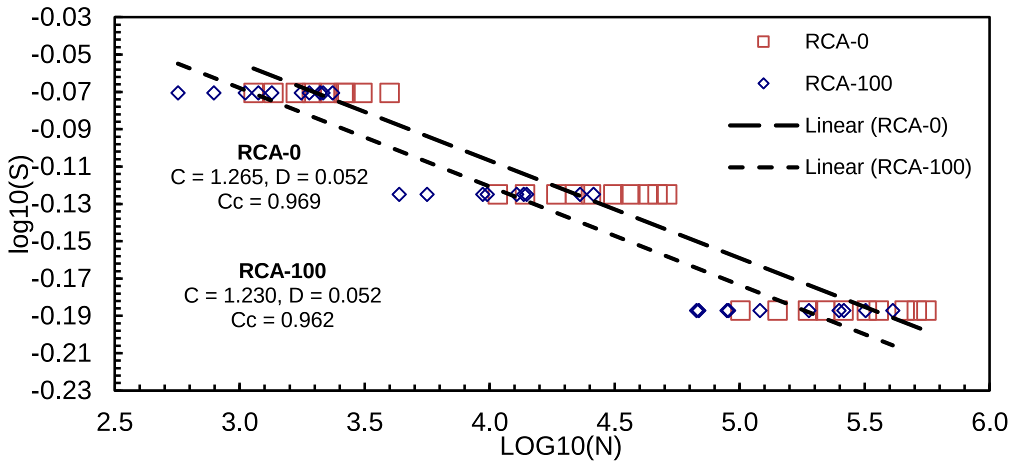

Figure 3 Estimation of Material Coefficients *C* and *D* of Eq. (3) for Concrete Mixes RCA-0 and RCA-100

The experimental data of fatigue of all the three concrete mixes i.e. RCA-100 and RCA-0 tabulated in Table 3 was used to calculate the material coefficients of above three equations. The estimated values of the coefficients A_1 and A_2 of eq. (1) for concrete mixes RCA-100 were 1.123 & −0.090 respectively whereas for concrete mix RCA-0 the values of A_1 and A_2 were calculated to be 1.144 and −0.089 respectively. Similarly, the estimated values of material coefficient β of eq. (2) for concrete mixes RCA-100 and RCA-0 were 0.0656 and 0.0620, with respective standard deviations of 0.0103 and 0.0094, and with a coefficient of variation of 15.69% and 15.13%, respectively. The values of coefficients C and D of eq. (3) for RCA-100 and RCA-0 concrete mixes were calculated as 1.230 & 0.052 and 1.265 & 0.052 respectively. These estimated values of material coefficients were utilized to estimate the flexural fatigue strength of concrete made with RCA and NA.

Fatigue Strength Prediction Model representing S-N-P_f Relationships

It is well known that the fatigue life data exhibits large variability or scatter due to intrinsic unevenness of the material, at the same stress level, even under carefully controlled test procedures. The variability in the fatigue life of concrete made with RCA is more as compared to that of concrete made with 100% NA due to the inherent heterogeneity of RCA. Hence, the incorporation of probability of failure P_f into the fatigue test data is an important aspect. Therefore the probability of failure (P_f) has been incorporated in S-N relationships to obtain, analytically and graphically, the families of S-N-P_f relationships for all the concrete mixes tested in this investigation.

An expression to describe the S-N-P_f curves is given below [27, 28].

$$L_N = (10)^{-a_1 (S)^{a_2} (logN)^{a_3}} \quad (4)$$

where 'a_1', 'a_2' and 'a_3' are the experimental coefficients, S is stress level and 'L_N' is the survival probability which is equal to 1-P_f, where P_f is probability of failure. To graphically represent the S-N-P_f relationship, the survival function of two parameter Weibull distribution (eq. 5) is used

$$ln\left[ln\left(\frac{1}{L_N}\right)\right] = \alpha \ln(n) - \alpha \ln(u) \quad (5)$$

where α and u are the shape parameter and scale parameter of the Weibull distribution. After applying number of calculations on eq. (5), the coefficients 'a_1', 'a_2' and 'a_3' for RCA-100 and RCA-0 concrete mixes were estimated. The detail of calculation is given in somewhere else by the authors [29]. The equations for RCA-100 and RCA-0 were established and are given as under.

For concrete mix RCA-100

$$L_N = (10)^{-5.10\times10^{-8}} (S)^{33.67} (\log N)^{18.13} \quad (6)$$

For concrete mix RCA-0

$$L_N = (10)^{-2.23\times10^{-10}} (S)^{41.05} (\log N)^{22.54} \quad (7)$$

Three methods namely graphical method, method of moments and maximum likelihood estimate were employed to analyse the experimental fatigue data given in Table 3 for both the concrete mixes. These parameters were calculated to establish that the fatigue life data of both the concrete mixes can be modelled by two parameter Weibull distribution. The detailed results are presented somewhere else by the author [30], therefore only the average value of α and u obtained by various method for both concrete mixes is presented here in Table 4.

Table 4 Average Values of Weibull Distribution Parameters (α and u) of various Concretes by Different Methods at all Stress Levels (S) Tested

CONCRETE MIX	STRESS LEVEL (S)	DISTRIBUTION PARAMETERS	
		α	u
RCA-0	0.85	2.721	2582
	0.75	2.190	34168
	0.65	2.033	355239
RCA-100	0.85	2.556	1729
	0.75	1.867	15084
	0.65	1.598	213421

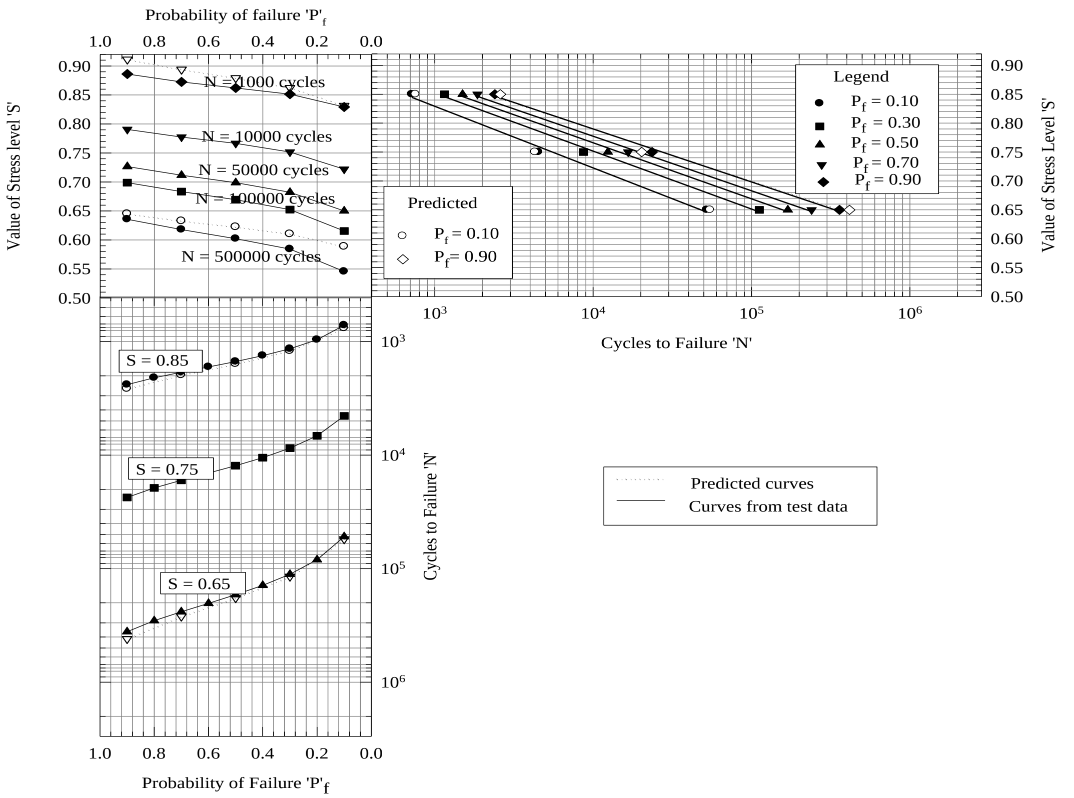

Figure 4 *S-N-P_f* curves for concrete mix RCA-100

S-N-P_f relationships have been established graphically by various researchers in the past for concrete made with NA [18, 27]. Therefore to develop a S-N-P_f relationship for RCA-100 concrete mix graphically, the similar procedure has been followed which was used earlier by various researchers. A family of such curves developed for RCA-100 concrete mix is shown in Figure 4. In the first step, a family of N–P_f curves has been generated by plotting the probability of failure, P_f, against the number of cycles to failure, N, corresponding to each stress level tested, as shown in the lower left part of the Figure 4. In the next step, a family of S–N curves has been plotted using the previously generated N–P_f curves. This is shown in the upper right part of Figure 4. Finally, the S–P_f curves have been plotted using previously generated S–N curves, as shown in the upper left part of Figure 4. Similarly, a family of curves for concrete made with NA, tested in the present study, has been generated and plotted in Figure 5. Using eqs. (6) and (7), some typical predicted curves have been plotted in Figure 4 and Figure 5, respectively, for RCA-100 and RCA-0 concrete mixes. It can be observed that predicted curves are fairly close to the experimental curves.

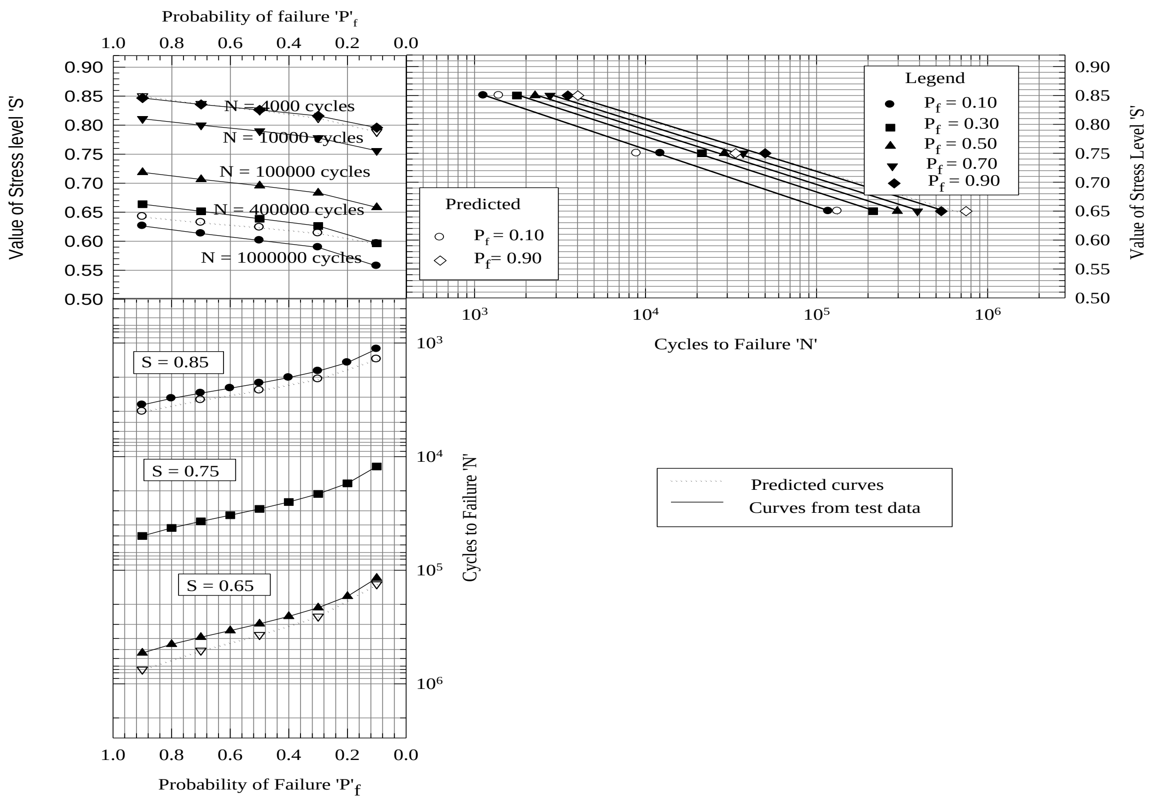

Figure 5 *S-N-P$_f$* curves for concrete mix RCA-0

Two Million Cycles Endurance Limit

The control concrete (RCA-0) shows the endurance limit of 58 percent of its static flexural strength. The comparison of *S-N* curves for RCA-100 mix with respect to RCA-0 mix has been shown in Figure 6. The predicted fatigue strengths for two-million cycles of load application for RCA-100 mix is 50% of the static flexural strength respectively. This shows that increase in content of RCA as replacement to NA reduced the two-million cycles fatigue strength of concrete.

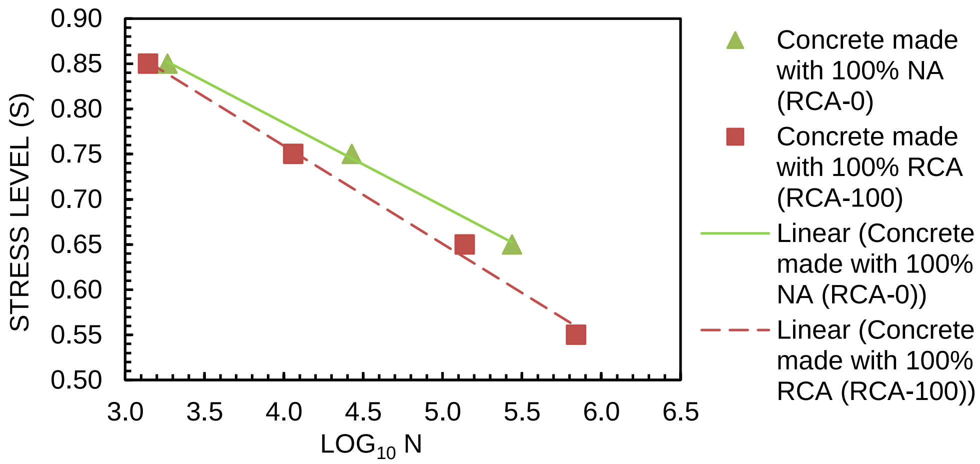

Figure 6 *S-N* curves for concrete mixes RCA-100 and RCA-0 based on stress as percentage of static flexural strength

CONCLUSIONS

The investigation shows the flexural fatigue performance of concrete mix containing 100% RCA and their comparison with that of concrete made with 100% NA through experimental and theoretical results. The experimental coefficients for RCA-100 concrete mix were calculated by using the coefficients which were used earlier to predict flexural fatigue strength of concrete made with 100% NA, thus making these equations applicable for concretes made with RCA. The fatigue test data have also been used to develop S–N–P_f relationships for RCA-100 concrete mix, both graphically and analytically, thus establishing a relationship between stress level, fatigue life and survival probability. It is concluded from the fatigue results obtained that the RCA-100 mix performed relatively poor comparison to RCA-0 concrete mix, thus necessitating the need for improving the flexural fatigue performance of concrete made with RCA. The work in this direction is currently in progress in the author's Institute with the use of cement additions such as metakaolin and silica fume as partial replacement of PC. However, it is assumed that the results obtained might have a few limitations when predicting fatigue lives with regard to structural applications of concrete made with RCA because the investigation was based upon small sized specimens.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the staff of the Concrete Structures Laboratories at Dr B R Ambedkar National Institute of Technology, Jalandhar, India during the experimentation work reported in the present investigation.

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