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Probability of Flexural Fatigue Failure of Concrete made with Recycled Concrete Aggregates

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Abstract. The paper presents results of an investigation conducted to quantify the flexural fatigue performance of concrete in which the Coarse Natural Aggregates (NA) were systematically replaced with Coarse Recycled Concrete Aggregates (RCA). Concrete mix containing 100% NA was also tested for comparison purpose. The compressive strength results of 100% RCA showed maximum reduction followed by the concrete made with 50% RCA. The fatigue test data of concrete made with 50% and 100% RCA and 100% NA was obtained by conducting flexural fatigue tests on beam specimens of 100×100×500 mm size. The specimens were tested using 100 kN MTS Servo-controlled actuator under four-point flexural fatigue loads applied at frequency of 10 Hz. Static flexural tests were also conducted to facilitate fatigue testing. The maximum flexural strength of 5.10 MPa was observed by the concrete mix containing 0% RCA (100% NA) followed by 4.89 MPa and 4.53 MPa for 50% RCA and 100% RCA respectively. 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 models for three concrete mixes have also been generated from the fatigue test data analytically. Two-Million cycles fatigue strength has also been estimated which was coming out to be 50% and 56% of the actual flexural strength for concrete mixes containing 50% and 100% RCA respectively.

1. 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 [2] 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. 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, 5, 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. 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 [7]. As reported earlier, there is a difference of about 17% 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 [8, 9].

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 [10]. Coarse Recycled Concrete Aggregates have high crushing and impact value than NA.

The concrete made with RCA shows up to 30% loss in compressive strength for 100% replacement of NA with RCA [11, 12]. 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% [13]. A similar behavior in splitting tensile strength has been observed in concrete made with RCA as in case of compressive strength [4]. However, some investigations indicated that concrete made with RCA either shows comparable or superior split tensile strength than that of concrete made with NA [14, 15]. 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 [13]. But, in general, it has been observed that there exists a decrease in the splitting tensile strength with the increase in the replacement levels of NA with RCA. 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 [16, 17].

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.

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 50% and 100% RCA as replacement of NA. A concrete mix containing 100% NA has also been made for the comparison purpose.

2. Experimental Programme

A total of 96 flexural fatigue tests and 72 complementary static flexural tests were executed on beam specimens of size 100mm × 100mm × 500mm under four-point flexural loading. A total of 72 compressive strength tests were also conducted on different batches of concrete to check the quality of each batch after 28 days of curing.

2.1. Mix proportions and materials used

In the present investigation three concrete mixes were cast based on the percentage replacement of NA with RCA. In the first concrete mix all the NA were replaced with that of RCA (RCA-100) whereas 50% of NA were replaced with RCA in the second concrete mix (RCA-50). A concrete mix containing 100% NA was also made for comparison purpose. Well graded RCA of size 12.5 mm (maximum)
with a specific gravity of 2.46, water absorption of 5.35%, aggregate impact value of 30.0% and aggregate crushing value of 25.6% were obtained from the demolished concrete specimens available in the concrete laboratory of the authors’ institute. Water absorption of 5.3% was obtained RCA Natural Aggregates of same size were obtained from the local market. Ordinary Portland cement (OPC) of 43 grade was used in the investigation. Locally available coarse sand was used as fine aggregates in this study. Class F fly ash (FA) with a specific gravity of 2.38 and fineness of 3280 cm\(^2\)/gm was used in all the concrete mixes as partial replacement of OPC. 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.

2.2. 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 x 150mm x 150mm and 7 beam specimens of size 100mm x 100mm x 500mm. The cube specimens were made to investigate the compressive strength of concrete at a curing age of 28 days whereas beam specimens were cast to investigate static flexure and flexural fatigue of concrete mixes approximately after 60 days of curing. Slump tests were performed to check the workability of all the concrete mixes and the observed slump was in a range of 60 mm to 90 mm. 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 0.55 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-50 were observed to be 31.70 MPa & 4.53 MPa and 34.23 MPa & 4.89 MPa respectively. Whereas value of average compressive strength and average flexural strength for concrete containing 100% NA (RCA-0) were observed to be 41.77 MPa and 5.10 MPa respectively.

| Mix Designation | Binder (OPC) (kg) | FA (kg) | RCA (kg) | NA (kg) | Water (liters) |
|-----------------|------------------|--------|----------|---------|---------------|
| RCA-0           | 343              | 148    | 762      | ----    | 1003          | 206           |
| RCA-50          | 343              | 148    | 762      | 468     | 501           | 206           |
| RCA-100         | 343              | 148    | 762      | 935     | ----          | 206           |

* (binder = OPC + FA)

3. Flexural Fatigue Test Results and Analysis
The fatigue test data obtained for concrete mixes RCA-100, RCA-50 and RCA-0 at different stress levels in this investigation is tabulated in table 2. Data points meeting the criterion for rejection as outliers were identified using Chauvenet’s criterion, and these were rejected and excluded from further analysis.

3.1. S-N models for the prediction of fatigue strength
These fatigue models have been used in the previous research studies [18, 19] 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, RCA-50).
First S-N relationship popularly known as Wohler’s equation is given as under:
\[ S = f_{\text{max}}(f_r)^{-1} = A_1 + A_2 \log_{10}(N) \]  
(1)

Where, \( f_{\text{max}}/f_r \) is Stress Ratio and \( A_1 \) & \( A_2 \) are the experimental coefficients.

**Table 2.** Fatigue Life Data (Number of Cycles to Failure, \( N \)) for Concrete Mixes RCA-0, RCA-50 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-50           |       |       |       |
| 688              | 7261  | 86887 |       |
| 982              | 9762  | 138405|       |
| 1041             | 10172 | 163781|       |
| 1128             | 12674 | 220108|       |
| 1429             | 16554 | 347947|       |
| 1673             | 20673 | 361778|       |
| 1931             | 23752 | 374560|       |
| 2176             | 29401 | 396702|       |
| 2294             | 32963 | 595673|       |
| 2567             | 39675 | ----  |       |
| 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

The second S-N relationship is called the modified form of Wohler’s equation \([18, 22]\) is given as under:

\[ S = f_{\text{max}}(f_r)^{-1} = 1 - \beta (1 - R) \log(N) \]  
(2)

where, \( \beta \) 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 \([23]\) written as

\[ S = f_{\text{max}}(f_r)^{-1} = C (N)^{-D} \]  
(3)
where, C and D are the experimental coefficients. The distinctive feature of equation (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 1: Estimation of Coefficients $A_1$ and $A_2$ of Equation (1) for Concrete Mixes RCA-0, RCA-50 and RCA-100

Figure 2: Estimation of Material Coefficients C and D of Equation (3) for Concrete Mixes RCA-0, RCA-50 and RCA-100

The experimental data of fatigue of all the three concrete mixes i.e. RCA-100, RCA-50 and RCA-0 tabulated in table 2 was used to calculate the material coefficients of above three equations. The estimated values of the coefficients $A_1$ and $A_2$ of equation (1) for concrete mixes RCA-100 and RCA-50 were $1.123$ & $-0.090$ and $1.113$ & $-0.085$ 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 $\beta$ of equation (2) for concrete mixes RCA-100, RCA-50 and RCA-0 were $0.0656$, $0.0637$ and $0.0620$, with respective standard deviations of $0.0103$, $0.0092$ and $0.0094$, and with a coefficient of variation of $15.69\%$, $14.37\%$ and $15.13\%$, respectively. The values of coefficients C and D of equation (3) for RCA-100 and RCA-50 concrete mixes were calculated as $1.230$ & $0.052$ and $1.213$ & $0.049$ respectively. Similarly the values of C and D for concrete made with 100% NA (RCA-0) were estimated to be as $1.265$ and $0.052$ respectively. Figure 1 and figure 2 shows the estimated values of material coefficients of all the three concrete mixes tested in the study. These estimated
values of material coefficients were utilized to estimate the flexural fatigue strength of concrete made with RCA and NA.

3.2. 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, the families of $S$-$N$-$P_f$ relationships for all the concrete mixes tested in this investigation.

An expression to describe the $S$-$N$-$P_f$ relationship is given below [24, 25]:

$$L_N = (10)^{-a_1 S^{a_2} (\log N)^{a_3}}$$  \hspace{1cm} (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 (equation 5) is used

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

where $\alpha$ and $u$ are the shape parameter and scale parameter of the Weibull distribution. After applying number of calculations on equation (5), the coefficients ‘$a_1$’, ‘$a_2$’ and ‘$a_3$’ for RCA-100, RCA-50 and RCA-0 concrete mixes were estimated. The detail of calculation is given in somewhere else by the authors [26, 27]. The three equations for RCA-100, RCA-50, and RCA-0 were established and are given as under.

For concrete mix RCA-100

$$L_N = (10)^{-5.10 \times 10^{-8} S^{33.67} (\log N)^{18.13}}$$  \hspace{1cm} (6)

For concrete mix RCA-50

$$L_N = (10)^{-1.90 \times 10^{-8} S^{37.77} (\log N)^{19.31}}$$  \hspace{1cm} (7)

For concrete mix RCA-0

$$L_N = (10)^{-2.23 \times 10^{-10} S^{41.05} (\log N)^{22.54}}$$  \hspace{1cm} (8)

Table 3. Average Values of Weibull Distribution Parameters ($\alpha$ and $u$) of various Concretes by Different Methods at all Stress Levels ($S$) Tested

| Concrete Mix | Stress Level ($S$) | Distribution Parameters | $\alpha$ | $u$ |
|--------------|-------------------|-------------------------|---------|-----|
| RCA-0        | 0.85              |                         | 2.721   | 2582|
|              | 0.75              |                         | 2.190   | 34168|
|              | 0.65              |                         | 2.033   | 355239|
| RCA-50       | 0.85              |                         | 2.638   | 1789|
|              | 0.75              |                         | 1.915   | 23139|
|              | 0.65              |                         | 1.667   | 315574|
| RCA-100      | 0.85              |                         | 2.556   | 1729|
|              | 0.75              |                         | 1.867   | 15084|
|              | 0.65              |                         | 1.598   | 213421|
Three methods namely graphical method, method of moments and maximum likelihood estimate were employed to analyse the experimental fatigue data given in table 2 for all the three concrete mixes. These parameters were calculated to establish that the fatigue life data of all the three concrete mixes can be modelled by two parameter Weibull distribution. The detailed results are presented somewhere else by the author [27], therefore only the average value of $\alpha$ and $\beta$ obtained by various method for three concrete mixes is presented here in table 3.

3.3. 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-50 and RCA-100 mixes with respect to RCA-0 mix has been shown in figure 3. The predicted fatigue strengths for two-million cycles of load application for the RCA-50 and RCA-100 mixes are 56% and 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 mixes RCA-50 and RCA-100 compared to concrete mix RCA-0.

![S-N Curves for Concrete Mixes RCA-50, RCA-100 and RCA-0 Based on Stress as Percentage of Static Flexural Strength](image)

4. Conclusions
The investigation shows the flexural fatigue performance of concrete mixes containing different percentages of RCA and their comparison with that of concrete made with 100% NA through experimental and analytical results. The experimental coefficients for RCA-100 and RCA-50 concrete mixes 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 different percentages of RCA. The fatigue test data have also been used to develop $S$-$N$-$P_f$ relationships for RCA-100 and RCA-50 concrete mixes, analytically, thus establishing a relationship between stress level, fatigue life and survival probability. It is concluded from the study that the RCA-50 concrete mix performed comparable to that of the RCA-0 concrete mix whereas RCA-100 concrete mix gave significant reduction in fatigue performance. However it is expected that RCA-50 and RCA-100 can perform better with the addition of a small amount of mineral admixtures in it. It is also 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.

5. References
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